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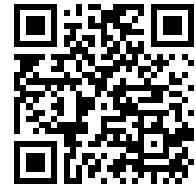

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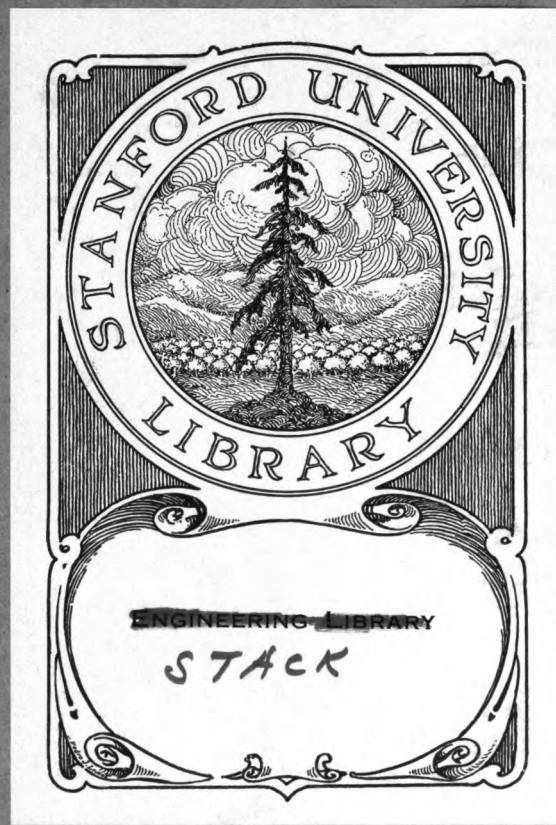

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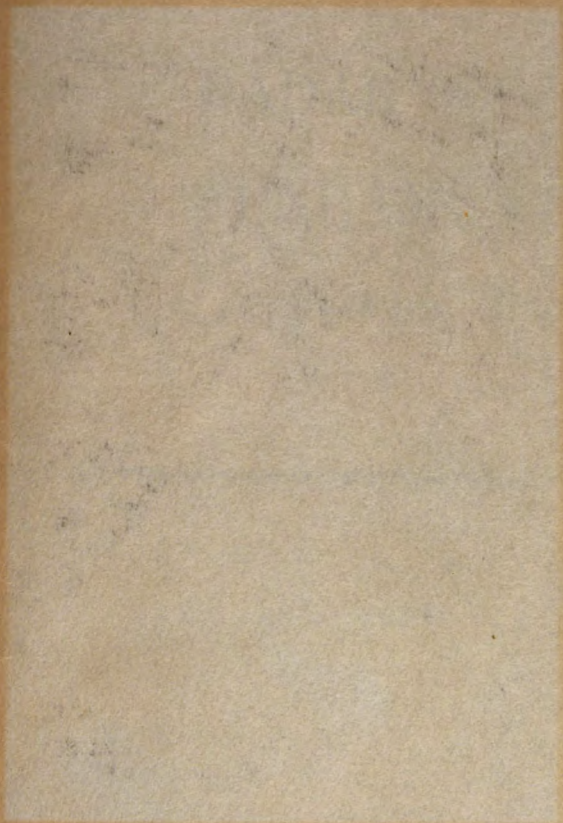

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RADAR SYSTEM FUNDAMENTALS

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WASHINGTON, D. C., APRIL 1944

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BUREAU OF SHIPS, NAVY DEPARTMENT,
Washington, D. C., 15 April 1944.

1. "Radar System Fundamentals," Navships 900,017 was written jointly by representatives of the Army and the Navy for the purpose of providing a ready reference on basic radar circuits.

2. Navships 900,017, "Radar System Fundamentals," is a confidential nonregistered publication and shall be handled, transported, and safeguarded in accordance with U. S. Naval Regulations. Periodic accounting is not required.

3. While the classification of this publication is necessarily Confidential, Commanding Officers are urged to make certain that the book is available to all radar personnel whose duties require access to the information contained therein.

4. The publication of this book was made possible through the cooperation of The Adjutant General, War Department; the Chief Signal Officer; the Commander in Chief, United States Fleet; and the Chief of Naval Personnel. It is issued by the Chief of the Bureau of Ships.

5. Additional copies of this publication (Navships 900,017), when required, should be requested from the Bureau of Ships, Code 903, Navy Department, Washington 25, D. C.

6. The publication Navships 900,016 referred to herein will be available approximately July 1944.

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Foreword

Radar System Fundamentals has been prepared jointly by the Army and the Navy for the purpose of providing the student technician with an understanding of typical radar circuits. It is anticipated that he will have become familiar with the subject coverage of either the radio technician courses and Navships 900,016 as furnished by the Bureau of Naval Personnel and Bureau of Ships respectively, or TM–1–455, TM 11–455, and TM 11–466 as provided by the War Department. No attempt has been made to provide an analysis of all the possible circuit combinations to be found in the various types of radar equipment in use in the services of the United States. However, it is believed that the choice of circuits presented here is sufficiently representative of all radar equipments to contribute materially toward the development of a more intelligent servicing technique.

The six functional components in the form of blocks, common to all radar sets, are introduced, and their inter-relationship is established. Actual circuits are then substituted for the functional blocks to present two complete equipments: one very simple long-wave set, followed by a representative microwave set. Six sections are then devoted to exploring the development of more highly refined circuits for improving the performance of the six basic functional components previously described. An additional section is provided in which the principles of servo mechanisms are presented. No complete production equipments have been utilized in the discussions covering the two representative radar sets. It is the practice of the services to provide with each specific production set one or more manuals which include a brief circuit analysis and tables of spare or replaceable parts, along with maintenance, servicing, installation, and operating data.

The majority of the circuits discussed in *Radar System Fundamentals* were extracted from various production equipments and in many cases were simplified in order to stress the fundamental operation. Particular reliance is placed on TM 11–466 and Navships 900,016 for the basic analysis of individual circuits composing the more complex radar circuits. Mathemetical considerations have been reduced to a minimum, as it is not anticipated that student technicians

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having access to this manual will be concerned with problems of design of radar equipment.

Consistent effort has been put forth throughout the manual to develop and establish a simple radar nomenclature in which terms of a descriptive nature have been given preference over those which convey no meaning to the beginner. In this respect a glossary of radar terms is provided in the appendix. Simple conventions have been used in preparing the circuit diagrams. The following conventions have been adopted with regard to values of circuit elements on diagrams:

Resistors		*Capacitors*	
150	= 150 ohms	.01	= 0.01 microfarad
150K	= 150,000 ohms	10	= 10 microfarads
1.5M	= 1,500,000 ohms	10$\mu\mu$	= 10 micromicrofarads

Lines which cross *without* being shown tied together by a *dot* form no contact. Lines which cross and *are* shown tied together by a *dot* form a contact. The direction of current flow has been considered to be the direction of the movement of electrons, that is, from negative to positive within the circuit and from cathode to plate within the vacuum tube.

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Section I
Elements of Radar

1. GENERAL.

a. Definition. Radar is an application of radio principles by means of which it is possible to detect the presence of objects, to determine their direction and range, and to recognize their character.

b. Principle. Detection is accomplished by directing a beam of radio frequency energy over a region to be searched. When the beam strikes a reflecting object, energy is reradiated. A very small part of this reradiated energy is returned to the radar system. A sensitive receiver located near the transmitter can detect the echo signal and therefore the presence of the object or target. The determination of the actual range and direction is based on the facts that radio-frequency energy travels at the constant velocity of light and that the receiving system can be made directional.

2. APPLICATIONS OF RADAR.

a. Search. (1) Tactical operations are based on the available knowledge of the enemy's dispositions and movements. Radar can be of extreme importance in providing a continuous flow of accurate information to the commanding officer. The initial location of the enemy and subsequent reports up to the time when action is finally joined is accomplished by search radar.

(2) The problem of locating aircraft targets differs from that of locating surface targets, in that the reflecting surface of an aircraft is small compared to that of a naval vessel. Also, since the speed of the aircraft is much greater, information is required at greater ranges in order to take effective action. This factor necessitates the use of *early warning* radar for aircraft search. Such systems are intended to determine range and approximate azimuth.

(3) The *accurate reporting* systems permit the location of the target more accurately than do the early warning systems. A means of measuring altitude is usually included in this type of equipment so that the target position is known in three dimensions. When the available data is used to direct fighter aircraft in the interception of the target, the name *ground controlled interception* (GCI) is sometimes applied.

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(4) The location of surface craft involves the determination of only their range and azimuth. *Surface search* radar is employed largely to provide the initial warning of the presence of such targets and to keep track of later movements. Since the speed of surface craft is relatively slow, exact data is not of great importance.

b. Fire control. (1) The problem of antiaircraft fire control requires accurate information on range, azimuth, and elevation. The maximum range of radar systems used for this purpose is limited to about 40,000 yards. The radar system is normally linked closely with the guns to be controlled because of the relatively short time during which an aircraft target is within firing range.

(2) The problem of fire control against naval vessels is simpler from the standpoint of determining position and because of the much lower speed of the target. Fire-control systems for use against surface targets measure range and azimuth only, but to a high degree of accuracy. The data is used to compute the firing problem, and the results may be used by widely separated gun batteries.

c. Airborne use. (1) One of the most important uses of radar is as an aid in the patrol of shipping lanes in search of enemy vessels. *Aircraft to surface vessels* (ASV) radar is able to increase the zone which can be searched by extending the range at which surface targets can be detected well beyond the visual limit. In addition, ASV provides an accurate means for guiding the patrol aircraft directly to the target.

(2) Fighter aircraft can be directed to the general vicinity of the enemy planes by means of early warning systems, but, unless conditions of visibility are adequate, they may completely miss the target. *Aircraft interception* (AI) equipment in the fighter plane permits the crew to locate the enemy at short ranges and to close to the attack. The additional weight of the equipment and the need for an operator requires a special fighter aircraft known as the "night fighter."

d. Identification—friend or foe. (1) Although radar can locate an object such as an aircraft or vessel accurately, it cannot distinguish between friend and enemy. This inability is particularly dangerous in fire-control systems, since the firing may be completely blind much of the time.

(2) Identification—friend or foe (IFF) equipment is used as an auxiliary to radar to identify friendly craft. The IFF system, located on the craft, receives from the radar location a challenging signal by radio means and returns a reply, either visually or by radio. IFF techniques are much the same as those of radar.

e. Navigational aids. (1) Radar is in itself a form of navigational equipment, since objects can be located with it. When the objects, such as mountains and prominent buildings, can be recog-

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nized, the movement of the vessel or aircraft can be guided accordingly.

(2) Radar *beacons* are used to supplement the natural fixed targets which act as reference points. Beacons are similar to IFF systems in that they receive signals from the radar set and return other signals to it. Each installation has its own code to identify its location. Therefore, the use of beacons is an improvement over the use of fixed targets.

(3) Radar *altimeters* are special radar systems used to measure the height above the surface of the earth. Such devices are called *absolute altimeters* because they measure the true distance to the earth without reference to sea level or barometric pressure. Since range is the only form of data required, and since the earth's surface is the target, altimeters are small and relatively simple.

3. RADAR METHODS.

a. Continuous-wave (c-w) method. One method of detecting a target makes use of the Doppler effect. When radio-frequency energy which is transmitted continuously strikes an object which moves toward or away from the source of energy, energy is reflected and its frequency is changed. The change in frequency is known as the Doppler effect. A similar effect at audible frequencies is recognized readily when the pitch of the whistle of a train is heard as it approaches or leaves the listener. The radar application of this effect measures the difference in frequency between the transmitted and reflected energy to determine the presence and speed of the moving target. This method works well with fast-moving targets, but not with those which are slow or stationary. C-w systems are therefore limited in present usage.

b. Frequency-modulation method. If the frequency of the transmitted energy is varied continuously and periodically over a specified band, the frequency of the energy being radiated by the antenna differs from that being received from the target. This difference occurs because of the time required for the energy to reach the target and return. The frequency difference depends on the distance traveled, and can be used as a measure of range. Moving targets produce a frequency shift in the returned signal because of the Doppler effect which affects the accuracy of range measurement.

c. Pulse-modulation method. The radio-frequency energy can also be transmitted in short pulses whose time duration may vary from 1 to 50 microseconds (millionths of a second). If the transmitter is turned off before the reflected energy returns from the target, the receiver can distinguish between the transmitted pulse and the reflected pulse. After all reflections have returned, the transmitter

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can again be turned on and the process repeated. The receiver output is applied to an indicator which measures the time interval between the transmission of the energy and its return as a reflection. Since the energy travels at a constant velocity, the time interval becomes a measure of the distance traveled or range. Since this method does not depend on the relative frequency of the returned signal or on the motion of the target, difficulties experienced in the c-w and frequency-modulation methods are not present. The pulse-modulation method is used almost universally in military and naval applications. Therefore it is the only method discussed in this manual.

4. DETERMINATION OF RANGE.

a. Time-range relationship. (1) The successful employment of pulse-modulated radar systems depends primarily on the ability to measure distance in terms of time. Radio-frequency energy, once

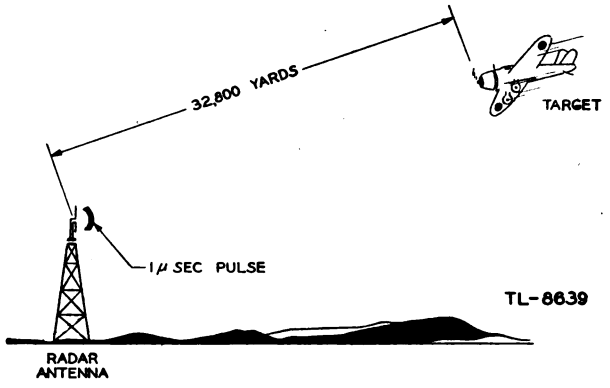

Figure 1. Pulse starts from antenna, elapsed time=0.

it has been radiated into space, continues to travel with a constant velocity. When it strikes a reflecting object there is no loss in time, but merely a redirecting of the energy. Its velocity is that of light, or, in terms of distance traveled per unit of time, 186,000 land miles per second, 162,000 nautical miles per second, or 328 yards per microsecond.

(2) The constant velocity of radio-frequency energy is applied in radar to determine range by measuring the time required for a pulse to travel to a target and return. For example, assume that a 1-microsecond pulse is transmitted toward an object which is 32,800 yards away. Figure 1 shows conditions at the instant the pulse is radiated. When the pulse reaches the target, it has traveled 32,800 yards at 328 yards per microsecond, and therefore 100 microseconds have elapsed. Figure 2 shows the pulse arriving at the target. The pulse is then reflected, and energy is returned over the same path. Since the

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return trip is also 32,800 yards, the required time of travel is again 100 microseconds. Figure 3 shows the pulse returned to the radar system. The total elapsed time is 200 microseconds for a distance traveled of twice the actual range of the target. For radar ranging therefore, the velocity is considered to be one half of its true value, or 164 yards per microsecond. In the example, range=time×164= 200×164=32,800 yards.

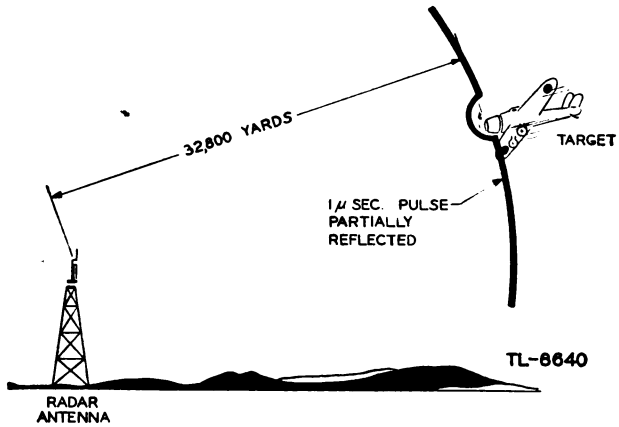

Figure 2. Pulse reaches target, elapsed time=100 μ seconds.

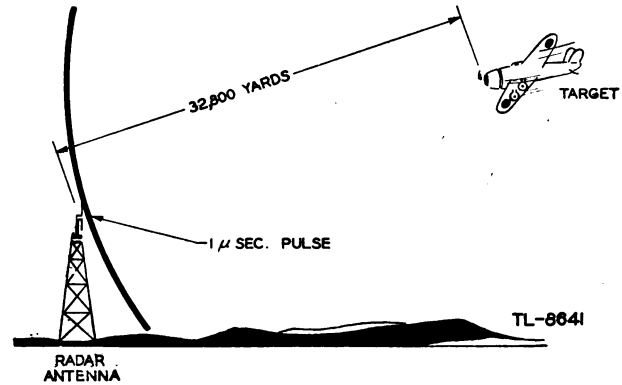

Figure 3. Pulse returns to radar, elapsed time=200 μ seconds.

b. Time measurement. (1) In order to employ the time-range relationship, the radar system must have a time-measuring device. In addition, since there may be more than one target in the region under search, some means of separating and identifying pulses must be included. The cathode-ray oscilloscope is well suited to such a task, since it retains the information on its screen and also forms a time scale. The time scale is provided by using a linear sweep to produce a known rate of motion of the electron beam across the screen of the cathode-ray tube.

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(2) The measurement of time is illustrated in the following example. Assume that a cathode-ray tube is used with a horizontal linear sweep which produces a beam whose velocity across the screen is 1 inch per 100 microseconds. The signals received from a target at a range of 32,800 yards are applied to the oscilloscope as a vertical deflection. Following the same sequence of operations as in the previous illustration, figure 4 shows the radio-frequency pulse leaving the radar antenna and the sweep just starting across the screen. Since 1 microsecond has elapsed, the leading edge of the pulse has moved 328 yards

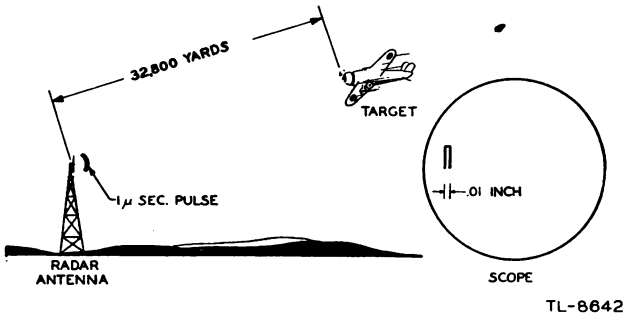

Figure 4.—Pulse leaves antenna, elapsed time=1 μ second.

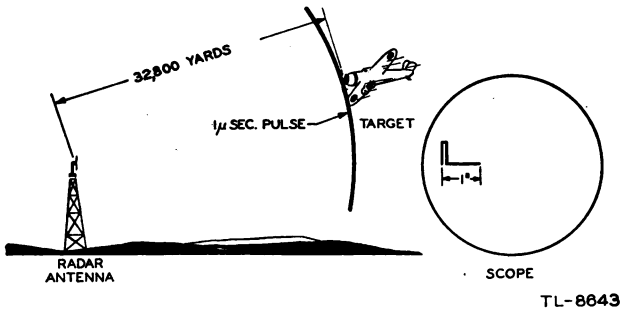

Figure 5. Pulse reaches target, elapsed time=100 μ seconds.

from the antenna, and the sweep trace has moved 0.01 inch across the screen. The pulse is shown on the screen as a vertical deflection, since the receiver detects the pulse which is supplied to the transmitting antenna. After 100 microseconds elapsed time the pulse reaches the target 32,800 yards away, and the sweep trace has moved 1 inch (fig. 5). Since the pulse energy is out at the target, there is no deflection of the trace vertically. The reflected pulse returns to the radar antenna at the end of 200 microseconds, during which the sweep trace has moved a total distance of 2 inches. For the length of the received pulse (1 microsecond) the trace is deflected vertically (fig. 6). Thus, with a constant sweep-trace velocity of 1 inch per

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100 microseconds, a time scale is produced which is equivalent to 100 microseconds times 164 yards per microsecond equals 16,400 yards per inch of trace. If another target returned the transmitted pulse in 300 microseconds, the return signal would be indicated 3 inches from the start of the sweep, and the range of the target would be $300 \times 164 = 49{,}200$ yards.

(3) The single-trace illustration used will not persist on the oscilloscope screen for sufficient time to be useful. Therefore it is necessary to repeat the pulse transmission and the sweep trace periodically.

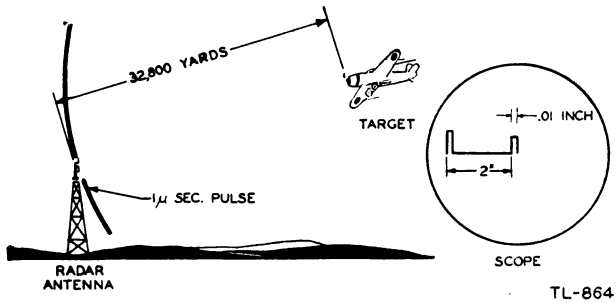

Figure 6. Pulse completes return to radar, elapsed time=201 μ seconds.

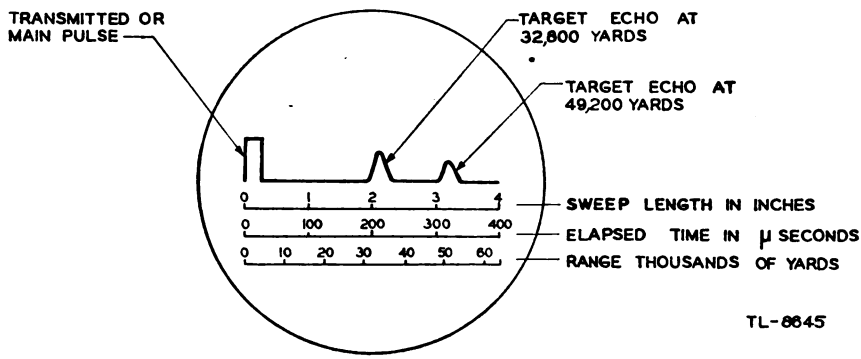
TRANSMITTED OR MAIN PULSE
TARGET ECHO AT 32,800 YARDS
TARGET ECHO AT 49,200 YARDS
0 1 2 3 4
SWEEP LENGTH IN INCHES
0 100 200 300 400
ELAPSED TIME IN μ SECONDS
0 10 20 30 40 50 60
RANGE THOUSANDS OF YARDS
TL-8645

Figure 7. Range indication of several targets. (Sweep-trace velocity is 1 inch/100 μ seconds.)

If the two operations are made to start in the same time relation each time, signals returned from a given target will be superimposed on each other by successive sweep traces. The signals from all targets will be shown on the oscilloscope in their proper sweep-time-range positions (fig. 7).

5. DETERMINATION OF AZIMUTH OR BEARING.

a. General. (1) The measurement of the direction of a target from the radar system is usually given as an angular position. The angle may be measured from true north if the installation is station-

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ary, or with respect to the heading of a vessel or aircraft containing the radar set. The angle at which the echo signal returns is measured by utilizing the directional characteristics of the radar antenna system.

(2) The dimensions of the individual radiating element (the dipole) cause it to send out more energy in some directions than in others. When several elements are used together to form an antenna system, the energy is further concentrated. Radar antennas are constructed of radiating elements, reflectors, and directors to produce a single narrow beam of energy in one direction. The pattern produced in this manner permits the beaming of maximum energy in a desired direction.

(3) The transmitting pattern of an antenna system is also its receiving pattern. An antenna can therefore be used to transmit energy, to receive reflected energy, or both.

b. Single-lobe system. (1) The simplest form of antenna for measuring azimuth or bearing is one which produces a single-lobe pattern. The system is mounted so that it can be rotated. Energy is directed across the region to be searched, and the beam is scanned in azimuth until a return signal is picked up. The position of the antenna is then adjusted to give maximum return signal.

(2) Figure 8 shows the receiving pattern for a typical radar antenna. In it, relative signal strength is plotted against angular position of the antenna with respect to the target. A maximum signal is received only when the axis of the lobe passes through the target.

(3) The sensitivity of the single-lobe system depends on the angular width of the lobe pattern. The operator adjusts the position of the antenna system for maximum received signal. If the signal strength changes rapidly with angular rotation, the accuracy with which the on-target position can be selected is great. Thus, in figure 9, the relative signal strengths "*A*" and "*B*" have very little difference. If the energy is concentrated into a narrower beam, the difference is greater and the accuracy better.

c. Double-lobe systems. (1) Figure 9 shows that the signal strength varies more rapidly on the side of the lobe than near the axis. The greatest rate of change of signal strength per degree of rotation occurs between the angles which give 50 and 85 percent of maximum. Radar systems designed for gun laying or fire control require the highest possible accuracy in measuring azimuth angles. The double-lobe system achieves this accuracy by using two lobes to form the antenna-system pattern.

(2) The principle of the double-lobe system is illustrated by using two separate antennas whose lobe axes are displaced by some angular distance (fig. 10). The two lobe patterns intersect at one point only,

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known as the crossover point, at which equal signals are produced by the two antennas for this particular azimuth. At all other positions of the array unequal signals are produced. When the target is in

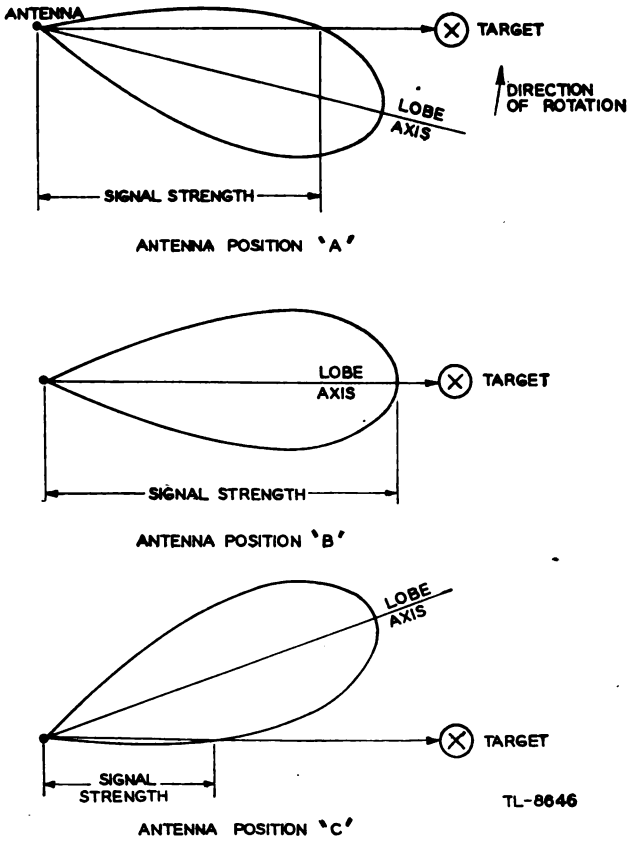

Figure 8. Relationship between beam axis and target bearing.

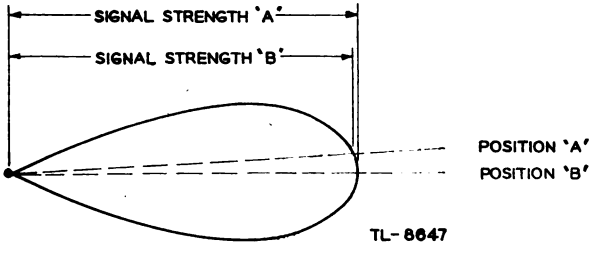

Figure 9. Accuracy of single lobe.

position A, the echo signal strength as received by lobe 1 is proportional to Y, and as received in lobe 2 is proportional to X. If the antenna is rotated so that the target is in position B, the signal from

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lobe 1 decreases to an amplitude proportional to X, while that from lobe 2 rises to a value proportional to Y. At position C, between these two positions of the antenna, the signals from the two lobes are equal and proportional to Z and the antenna system is on the bearing of the target.

(3) The use of two lobes instead of a single lobe greatly increases the accuracy of azimuth measurement. The amount of increase depends on the configuration of the antenna array. In general, the increase is at least five times, but it can be much greater. In addition to the greater accuracy of the double lobe, there is another advantage in the sense of direction available. If the antenna array is *off-target* on the side of lobe 1 (fig. 10, position A) the signal received by lobe 1 is the larger. Therefore the antenna should be rotated toward the left until the signals become equal. When the amplitude of each signal is proportional to Z, the antenna is said to be *on-target*.

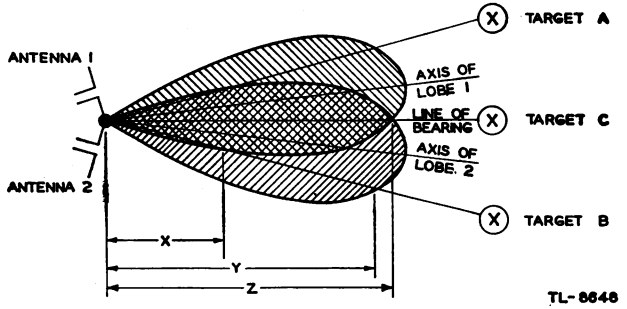

Figure 10. Double-lobe pattern.

6. DETERMINATION OF ELEVATION.

a. General. (1) The remaining dimension necessary to locate completely an object in space can be expressed either as an angle of elevation or as an altitude. If one is known, the other can be calculated from the right-triangle relationship and the slant range (fig. 11).

(2) The free-space pattern of an antenna array is based on the arrangement of the individual elements within the system. If the same array is placed close to the earth, however, the vertical free-space pattern may be changed by the effect of ground reflections. Figure 12 represents an antenna above the earth which has been elevated sufficiently so that energy will not strike the earth's surface and be reflected. Therefore the only energy that reaches the target is that which comes directly from the antenna system. If the antenna beam is lowered to the position shown in figure 13, some of the transmitted energy hits the earth and is reflected back into space. The target now receives energy from two directions and the effective field is the sum

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of the two fields so produced. The reflected wave travels further than the direct ray in reaching the target. The addition of the fields at the target depends on the difference in the distances traveled expressed in wavelengths. For example, if the path difference for a given target

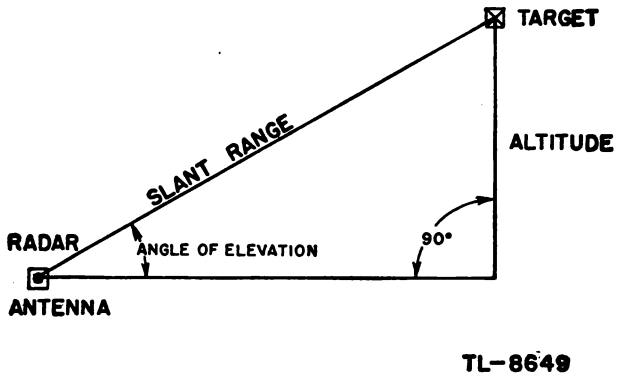

Figure 11. Determination of altitude.

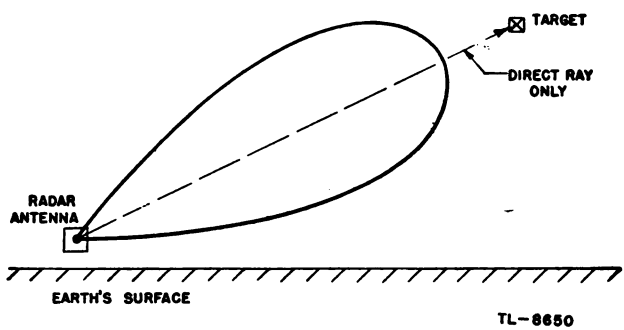

Figure 12. Antenna elevated to avoid ground reflections.

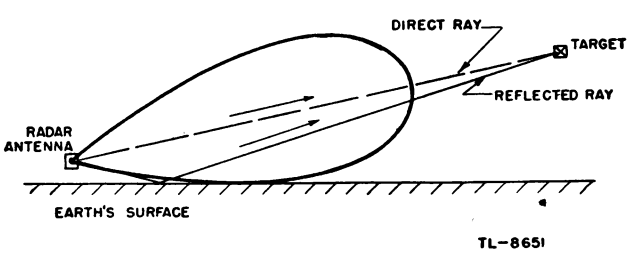

Figure 13. Reflection of transmitted energy by surface of earth.

position is a half wavelength, the fields cancel. If the position of the target is changed so that the path difference is a full wavelength the fields add. The result of ground reflection is to break the single free-space lobe into a number of smaller lobes, with gaps between them. Figure 14 illustrates this effect.

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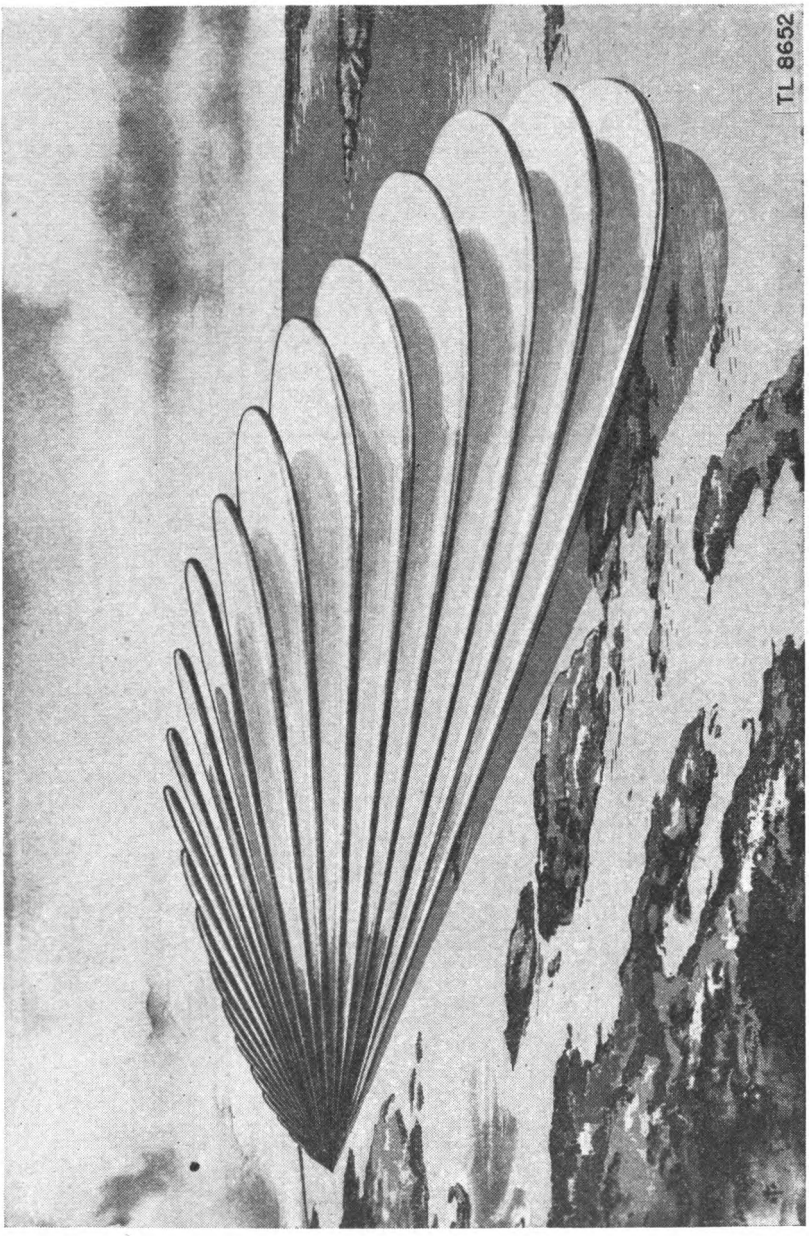

Figure 14.—Typical vertical-coverage pattern.

b. Methods. (1) Any method used for determining the angle of elevation or the altitude must either make use of ground reflections or completely avoid them. The *threshold-pickup* method and the *signal-comparison* method use the effect of ground reflections to find altitude. The *tilted-antenna* method avoids ground reflections and measures the angle of elevation.

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(2) The threshold-pickup method makes use of the vertical-coverage pattern of an antenna system whose lobe axis is parallel to the earth. The positions of the lobes and gaps are determined by flying an aircraft toward the radar installation on known altitudes, and recording the ranges at which a minimum usable signal is returned. A typical plot of this data is shown in figure 15. The chart obtained in this way is used by observing the range at which an unknown target first appears, and then reading its altitude from the chart. This method is very inaccurate, primarily because the graph of the antenna pattern is determined by the use of a single aircraft while the target may be any number of planes. In general, the greater the number of planes, the greater is the strength of the returned signal. Therefore, a large flight of planes at a given altitude will be detected at a greater range than a single plane.

(3) The signal-comparison method is simply an extension of the threshold-pickup method. Two antennas are placed one above the

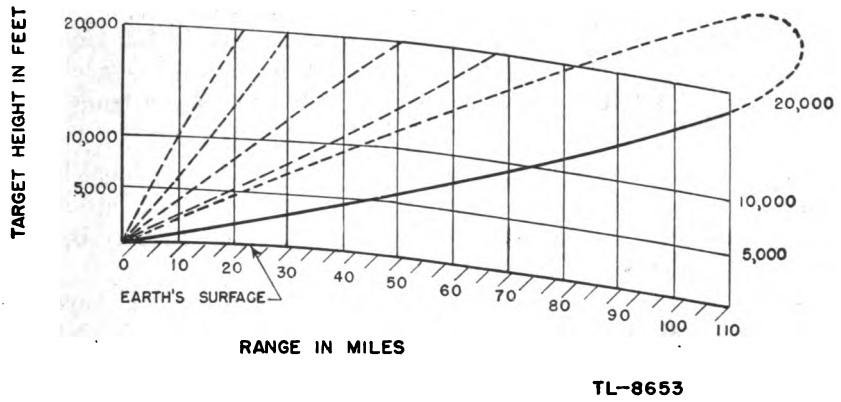

Figure 15.—Calibration chart for estimating aircraft altitude.

other to give slightly different vertical-coverage patterns. The lobes therefore overlap but do not coincide. The signals received on the two antennas are compared in magnitude, and their ratio, together with the range of the target, is applied to a height-range chart from which altitude is read. Under favorable conditions, the altitude can be determined within 500 feet. Inaccuracies due to the number of planes in a given target are largely eliminated because a ratio is used.

(4) The tilted-antenna method measures the angle of elevation directly in the same way that azimuth is measured. Ground reflections are avoided by using the system on targets which are high enough so that transmitted energy does not strike the ground (fig. 12). The accuracy of this method depends on the free-space pattern and the ability of the operator to locate the on-target position of the antenna array. Double-lobe systems are commonly used to increase the precision with which the antenna is pointed.

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Section II
Functional Components of Radar System

7. FUNDAMENTAL ELEMENTS.

a. General. Radar systems now in existence vary greatly as to detail. They may be very simple or, if more accurate data are required, they may be highly refined. The principles of operation, however, are essentially the same for all systems. Thus a single basic radar system can be visualized in which the functional requirements hold equally well for all specific equipments. The varying details are due to a choice of specific circuits to fulfill these general functional requirements. In general, the degree of refinement of these circuits increases with the frequency, since the microwave region lends itself to a higher degree of precision in angular measurement.

b. Functional block diagram. (1) The functional breakdown of the pulse-modulated radar system resolves itself into six essential components. These are shown in figure 16 and may be summarized as follows:

(*a*) The *timer* (variously known as the synchronizer, keyer, or control central) supplies the synchronizing signals which time the transmitted pulses and the indicator, and which coordinate other associated circuits.

(*b*) The *transmitter* generates the r-f energy in the form of short, powerful pulses.

(*c*) The *antenna system* takes the r-f energy from the transmitter, radiates it in a highly directional beam, receives any returning echoes, and passes these echoes to the receiver.

(*d*) The *receiver* amplifies the weak r-f pulses returned by the target and reproduces them as video pulses to be applied to the indicator.

(*e*) The *indicator* produces a visual indication of the echo pulses in a manner which furnishes the required information.

(*f*) The *power supply* furnishes all a-c and d-c voltages necessary for the operation of the system components.

(2) Any radar system can be subdivided on the basis of the functional block diagram presented in figure 16. An actual system may contain several functional components within one physical component, or a single function may be performed in several physical components.

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However, the analysis of the operation of a given set is greatly simplified by applying the functional block diagram without considering the physical location of the circuits.

8. SYSTEM CONSTANTS.

a. General. Any radar system has associated with it certain constants. The choice of these constants for a particular system is determined by its tactical use, the accuracy required, the range to be covered, the practical physical size, and the problem of generating and receiving the signal.

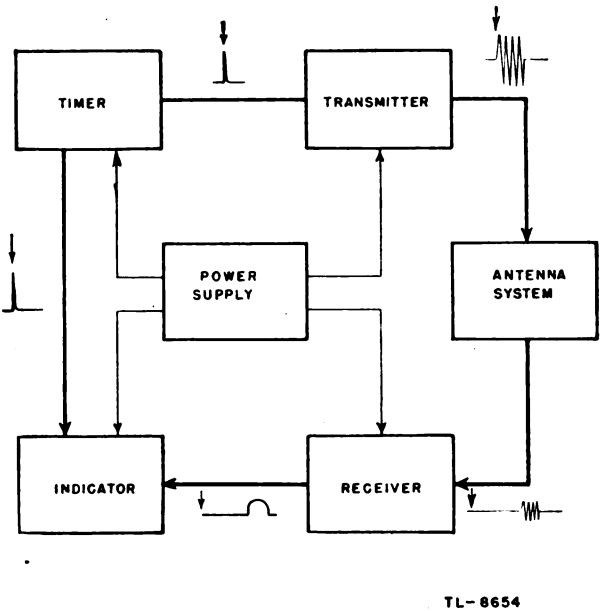

Figure 16. Functional block diagram of fundamental radar system.

b. Carrier frequency. (1) The carrier frequency is the frequency at which the radio energy is generated. The principal factors influencing the selection of the carrier frequency are the desired directivity and the generation and reception of r-f energy.

(2) For the determination of direction and for the concentration of the transmitted energy so that a greater portion of it is useful, the antenna should be highly directive. The higher the carrier frequency, the shorter the wavelength and hence the smaller is the antenna array for a given sharpness of pattern, since the individual radiating element is normally a half-wave long. For an antenna array of a given physical size the pattern is sharper for a higher frequency.

(3) The problem of generating and amplifying reasonable amounts of radio energy at extremely high frequencies is complicated by the

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physical construction of the tubes to be used. The common triode becomes impractical and must be replaced by tubes of special design. Among these are such types as the "lighthouse" triode, the grounded-grid triode, the klystron, the magnetron, and the "doorknob," "acorn," and "peanut" tubes. In general, the modifications are designed to reduce interelectrode capacitances, transit time, and stray inductance and capacitance in the tube leads.

(4) The lowest carrier frequency normally used is 100 megacycles per second, in order to limit the antenna array to a practical size and yet to obtain the desired directional beam. Frequencies from 100 to 3,000 megacycles are in general use. Toward the upper end of this band ranges are somewhat reduced because of inherent difficulties in generating and amplifying r-f energy at extremely high frequencies. Sets have been designed to operate up to and beyond 10,000 megacycles in order to produce very narrow beams or to reduce the antenna size.

c. Pulse-repetition frequency. (1) Sufficient time must be allowed between transmitted pulses for an echo to return from any target located within the maximum workable range of the system. Otherwise the reception of the echoes from the more distant targets will be obscured by succeeding transmitted pulses. This necessary time interval fixes the highest frequency which can be used for the pulse repetition.

(2) When the antenna system is rotated at a constant speed, the beam of energy strikes a target for a relatively short time. During this time, a sufficient number of pulses of energy must be transmitted in order to return a signal which will produce a lasting indication on the oscilloscope screen. The persistence of the screen and the rotational speed of the antenna therefore determine the lowest repetition rate that can be used.

(3) In a system in which the entire interval between transmitted pulses is used in the indicator, the repetition frequency must be very stable if accurate range measurement is desired. Since the oscilloscope screen will normally have a fairly long persistence, successive traces should appear in exactly the same position to avoid blurring.

d. Pulse width. The minimum range at which a target can be detected is determined largely by the width of the transmitted pulse. If a target is so close to the transmitter that the echo is returned to the receiver before the transmitter is turned off, the reception of the echo obviously will be masked by the transmitted pulse.

e. Power relation. (1) A radar transmitter generates radio-frequency energy in the form of extremely short pulses and is then turned off between pulses for comparatively long intervals. The useful power of the transmitter is that contained in the radiated pulses

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and is termed the *peak power* of the system. Power is normally measured as an average value over a relatively long period of time. Since the radar transmitter is resting for a time which is long with respect to its operating time, the average power delivered during one cycle of operation is quite low compared to the peak power available during the pulse time.

(2) A definite relationship exists between the average power dissipated over an extended period of time and the peak power developed during the pulse time. The time of one cycle of operation is the reciprocal of the repetition frequency, $T=1/f$. Other factors remaining constant, the greater the pulse width the higher the average power; and the longer the pulse-repetition time the lower the average power. Thus:

$$\frac{\text{average power}}{\text{peak power}} = \frac{\text{pulse width}}{\text{pulse-repetition time.}}$$

These general relationships are shown in figure 17.

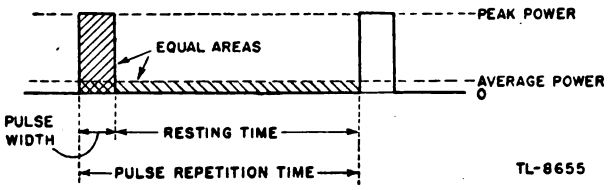

Figure 17. Relationship of peak and average power.

(3) The operating cycle of the radar transmitter can be described in terms of the fraction of the total time that the r-f energy is radiated. This time relationship is called the duty cycle and may be represented as—

$$\frac{\text{pulse width}}{\text{pulse-repetition time}} = \text{duty cycle}$$

For example, a 2-microsecond pulse repeated at the rate of 500 times per second represents a duty cycle of 0.001, since the time for 1 cycle is 1/500 second, or 2,000 miscroseconds:

$$\frac{2}{2{,}000} = 0.001 = \text{duty cycle}$$

(4) Likewise, the ratio between the average power and peak power may be expressed in terms of the duty cycle:

$$\frac{\text{average power}}{\text{peak power}} = \text{duty cycle}$$

In the above example it may be assumed that the peak power is 200 kilowatts. For 2 microseconds, then, 200 kilowatts of power are avail-

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able, while for the remaining 1,998 microseconds zero power is available.

Since:

$$\text{average power} = \text{peak power} \times \text{duty cycle}$$

Then

$$\text{average power} = 200 \times 0.001 = 0.2 \text{ kilowatts}$$

These relationships are shown in figure 18.

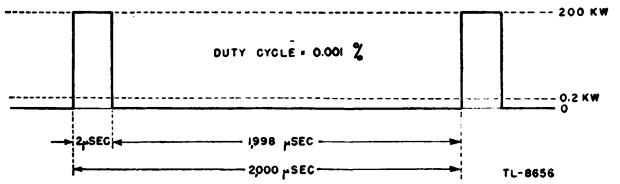

Figure 18. Duty cycle.

(5) High peak power is desirable to produce a strong echo over the maximum range of the equipment. Low average power enables the transmitter tubes and circuit components to be made smaller and more compact. Thus it is advantageous to have a low duty cycle. The peak power which can be developed is dependent upon the interrelation between peak and average power, pulse width and pulse-repetition time, or duty cycle.

9. TIMER.

a. General. The function of the timer is to insure that all circuits connected with the radar system operate in a definite time relationship with each other and that the interval between pulses is of the proper length. In general, there are two practical methods of supplying the timing requirements.

b. Timing by separate unit. The pulse-repetition frequency can be determined by an oscillator of any stable type such as a sine-wave oscillator, a multivibrator, or a blocking oscillator. The output is then applied to necessary pulse-shaping circuits to produce the required timing pulse. Figure 19 shows several typical combinations of circuits which may be used. The timing of associated components can be accomplished with the output of the timer or by obtaining a timing signal from the transmitter as it is turned on.

c. Timing within transmitter. The transmitter, with its associated circuits, may establish its own pulse width and pulse-repetition frequency and provide the synchronizing pulse for the other components of the system. This action may be accomplished by a self-pulsing or blocking r-f oscillator with properly chosen circuit constants. This method of timing eliminates a number of special timing

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circuits, but the pulse width or pulse-repetition frequency obtained may be less rigidly controlled than is desirable for some applications.

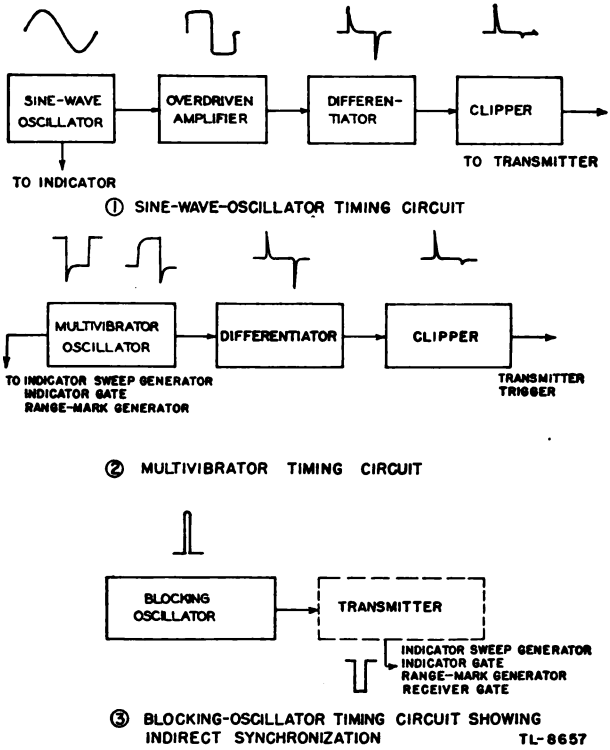

Figure 19. Representative methods of timing radar systems.

10. TRANSMITTER.

a. Self-pulsed system. In the self-pulsing radar transmitter the functions of transmitting and timing are carried out by one component (fig. 20). This type of transmitter in effect oscillates at two frequencies: the *carrier frequency*, as determined by the *LC* constants of the tank circuit, and the *pulsing frequency*, as determined by the *RC* constants of the grid circuit. The grid capacitor largely controls the width of the pulse in that its size determines the number of positive r-f swings required to charge it sufficiently to *block* the tube. The grid-leak resistor controls the pulse-repetition frequency to the extent that it determines the time required for sufficient charge to leak out of the grid capacitor to *unblock* the tube (the resting time). The timing pulse for other components is developed across a resistor in the cathode circuit of the blocking oscillator.

b. Externally pulsed system. In the externally pulsed type of radar transmitter the function of the r-f oscillator is relatively simple, that is, to generate powerful pulses of r-f energy at regular

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intervals. As the resting time is very long compared to the transmitting time, the oscillator may be greatly overloaded during transmission to increase the peak power. In this type of operation the r-f oscillator requires power in the form of a properly timed, high-amplitude, rectangular pulse. In most cases the timing oscillator cannot fulfill this requirement directly, and therefore it is necessary to use a driver and a modulator (fig. 21). A driver is any circuit which, when triggered, drives the modulator with a rectangular pulse of accurately timed width. A modulator is a circuit which supplies

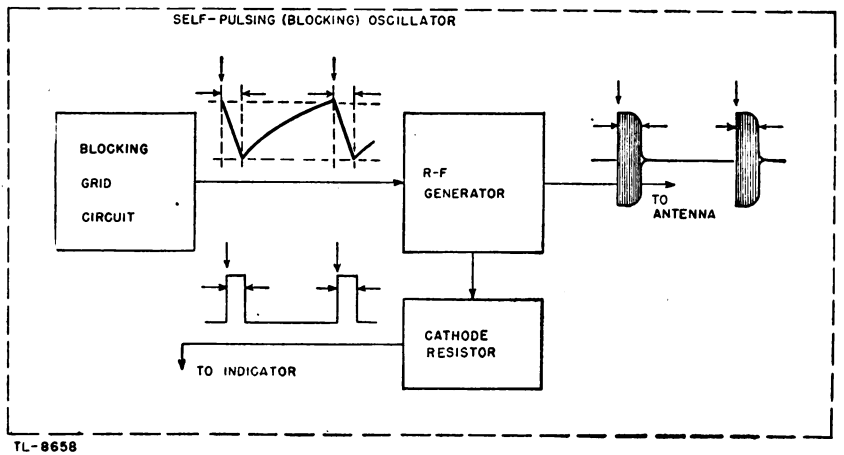

Figure 20. Self-pulsing oscillator functioning as transmitter and timer.

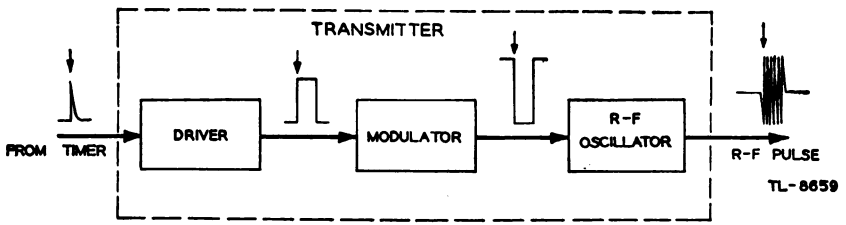

Figure 21. Externally pulsed transmitter.

power to the r-f oscillator in the form of a timed, high-amplitude, rectangular pulse. The driver is triggered by the timer in order to maintain the repetition rate of the system. The driver, when triggered, shapes a rectangular pulse of proper time duration which in turn operates the modulator. The modulator then furnishes the high plate voltage to the r-f oscillator for the predetermined pulsing time. Thus the transmitter function may be carried out by the combined performance of a driver, a modulator, and an r-f oscillator. The modulator acts like a power amplifier for the driver and like a switch for the r-f oscillator.

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11. ANTENNA.

a. General. (1) The function of the antenna system is to take the energy from the transmitter, radiate it in a directional beam, pick up the returning echo, and pass it to the receiver with a minimum of losses. The antenna system may be considered to include the transmission lines from the transmitter to the antenna array, the antenna array itself, the transmission line from the antenna array to the receiver, and any antenna-switching device and receiver-protective device which may be present.

(2) When a radar receiver is operated in close proximity to a powerful radar transmitter, a certain amount of signal inevitably finds its way into the receiver directly from the transmitter by way of the stray capacitance of the input circuit leads. In certain instances such signals resulting from the main transmitted pulse must be entirely eliminated from the output of the receiver. Therefore the receiver must be gated or turned off during the pulse time so that it may be completely insensitive.

(3) It may be desirable to couple a small amount of the transmitted r-f energy to the receiver for timing purposes. However, the signal directly available from the transmission line is so strong that the receiver input circuit may be burned out. Because of the sensitivity of the receiver, the strong signal may also cause blocking of tubes which employ R-C grid circuits. This blocking occurs because the strong signal will overdrive the tubes, causing grid current to flow which charges the capacitors. After the signal is removed the charge remains for some time as a bias which is much greater than cut-off. Both of these conditions place a limit on the permissible amount of transmitted pulse which can reach the receiver, and are the reasons for employing receiver-protective devices.

b. Use of two antennas. The simplest radar antenna system would contain two separate antenna arrays: one for transmitting and one for receiving (fig. 22). In this arrangement the receiving antenna must be shielded from the transmitting antenna in order to protect the receiver from the powerful pulses of energy being radiated. In general, the directivity of the antennas is sufficiently great to permit the location of the receiving antenna in a minimum signal region of the transmitting pattern. In aircraft installations the fuselage can be used to shield the receiving antenna from the transmitting antenna.

c. Use of single antenna and switch. (1) A more practical radar system employs a single antenna and an antenna switch capable of connecting the antenna to the transmitter during the transmission time and to the receiver during the remainder of the pulse cycle. The switch is necessary to protect the receiver from the transmitter during the pulse time and also to isolate the transmitter during

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the receiving time. Otherwise the weak echoes might be wholly or partially lost in following the transmission line back to the transmitter. The transmitted pulse width and the repetition frequency of the system, which may range from 60 to 4,000 cycles per second, eliminates the possibility of using a mechanical switch. Otherwise a double-pole, double-throw switch (fig. 23) would serve the purpose.

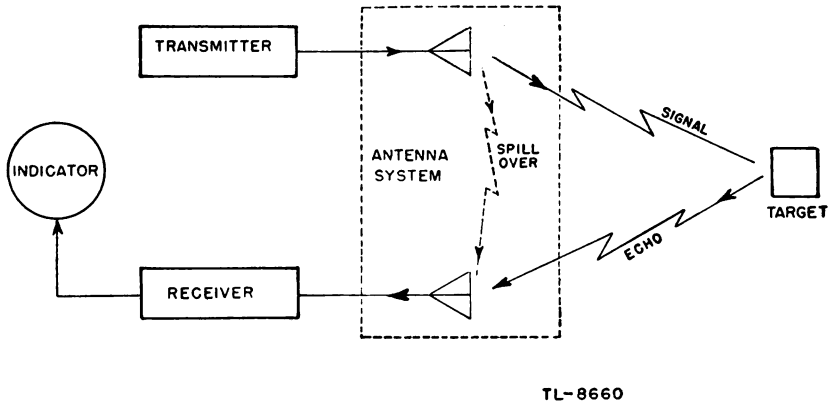

Figure 22. Simple antenna system using separate antennas for transmitting and receiving.

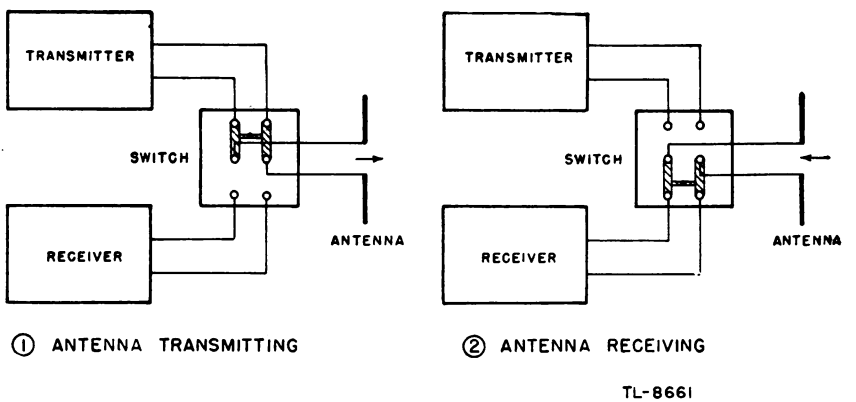

Figure 23. Antenna switch.

(2) A system for using the single antenna for both transmission and reception should be as efficient as possible. In other words, all of the energy produced by the transmitter should reach the antenna, and all of the received energy should reach the receiver. This efficiency is most easily obtained by matching the antenna to the characteristic impedance of the transmission line. During transmission of the pulse, the transmitter should be matched to the transmission line and the receiver must present an open circuit or high impedance to the

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transmission line. During the reception time the conditions should be reversed.

(3) The problem of switching is usually simplified because most transmitters have a different output impedance when they are on than when they are off. If properly matched to the transmission line during the pulse, the transmitter will be mismatched for the receiving time, and the transmission line will become resonant. Figure 24 illustrates a typical elementary system in which the receiver and transmitter are connected by branch lines to the antenna feed line. The junction of the three lines is known as the T-junction. During the off period, the switch in the receiver branch is closed and the transmission line from antenna to receiver is properly matched. The resistance seen from the T-junction looking toward the transmitter can be controlled by the length of the resonant section between them. If the transmitter im-

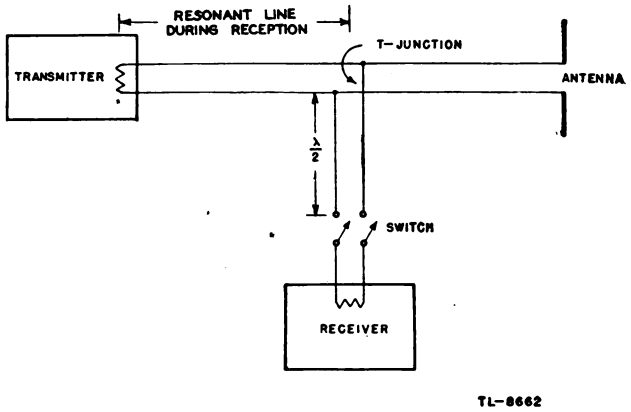

Figure 24. Elementary switching system.

pedance decreases when it is turned off, the length should be a quarter-wavelength, or some odd multiple thereof, in order to see a high impedance. The high impedance presented by the transmitter and its feed line to the T-junction is in parallel with the relatively low characteristic impedance of the remainder of the transmission line system, but, being high, has little effect. If the transmitter impedance increases when it is turned off, the resonant-line length should be a half-wavelength, or a multiple thereof.

(4) When the transmitter is turned on to transmit the next pulse, it again will be properly matched to the antenna. The open switch (fig. 24) will prevent the pulse from reaching the receiver, and will cause a mismatch to the line between the switch and T-junction. By using some multiple of a half-wavelength, the open circuit of the switch will be presented as an open circuit across the transmitter-antenna line.

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(5) In a broad sense, then, the switching problem consists of providing what amounts to a double-pole, single-throw switch (fig. 24) for connecting the antenna alternately to the transmitter and to the receiver. The swiching device must be capable of acting within a time interval of a few microseconds, as the receiver should be in the antenna circuit immediately after the transmission of the pulse in order to detect close-range targets. This microsecond timing requires that the device be electronic in type. Under various operational circumstances it may take the form of r-f amplifiers, klystrons, spark gaps, resonant transformers, spark-gap tubes, and (in waveguides) resonant slits. It is commonly known as the T-R (transmit-receive) switch or T-R box. Other terms frequently encountered are *duplexer*, *reprod*, and, in certain instances, *polyplexer*.

d. Types of radiators. (1) The principal types of radiators employed in the radar antenna system include: the stacked-dipole array with untuned reflector the dipole with tuned reflectors and di-

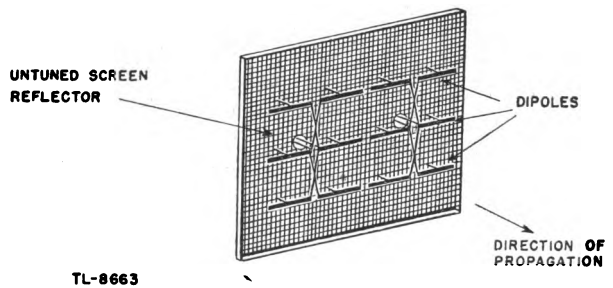

Figure 25. Typical stacked-dipole array.

rectors (Yagi), the dipole with parabolic reflector, and various arrangements of dielectric radiators used in conjunction with waveguides.

(2) Figure 25 shows a typical stacked-dipole array. This type of array may be composed of one or more banks of dipoles and may be adapted for lobe switching. The entire assembly usually can be rotated in either azimuth or elevation, or both.

(3) Figure 26 shows a type of Yagi array utilizing both director and reflector parasitic antennas in conjunction with a driven element. Only the driven element is connected to the transmission line. The other elements are excited parasitically, picking up energy from the driven element and reradiating it with such a phase relation with respect to the driven dipole that the field is reinforced in the forward direction.

(4) Figure 27 shows the parabolic-reflector type of antenna, which is a practical means of producing a narrow beam pattern in the region

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of the micro-wavelengths. The reflection of r-f energy by the parabola or *dish* is closely analogous to the reflection of light by a parabolic mirror. The dish is large in comparison with the operating wavelength; in general, the larger the reflector, the narrower the beam

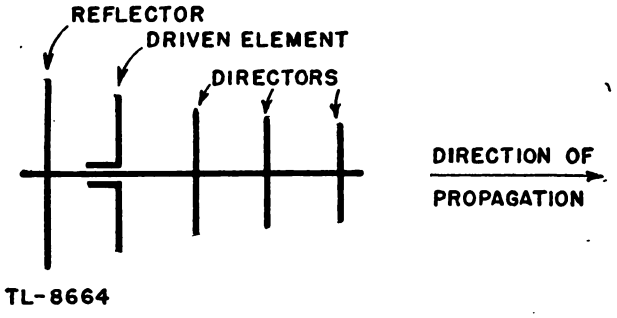

Figure 26. Yagi array.

pattern. The r-f energy is fed to a dipole located at the focal point of the parabola. A parasitic reflector is placed about one quarter-wavelength in front of the dipole, to reflect practically all of the ra-

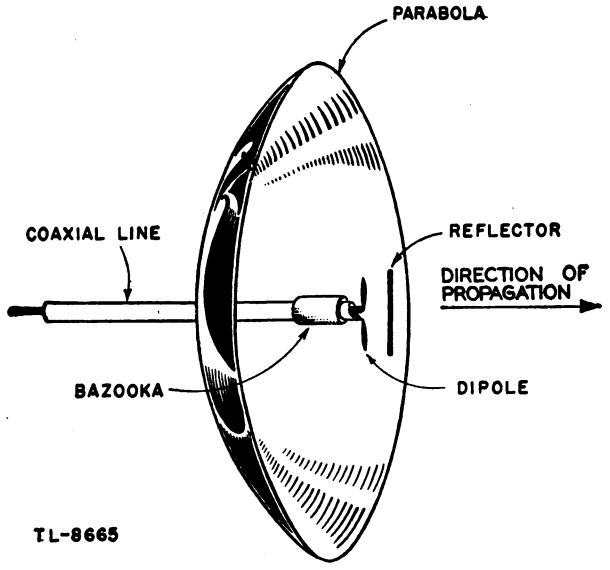

Figure 27. Dipole with parabolic reflector.

diated energy back to the dish from which it is reflected ahead in the form of a narrow beam. Modifications of this type of radiating system include cylindrical and other types of parabolas. Parabolic reflectors are frequently used in conjunction with waveguides.

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(5) Figure 28 shows a type of application of dielectric radiators fed by waveguides. These radiators may be considered to be merely extensions of the waveguides and are designed to provide the proper termination to transfer the energy from the waveguides to space.

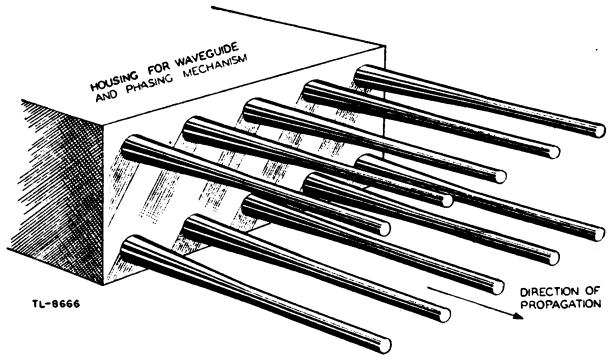

Figure 28. Bank of dielectric radiators each of which is fed by a waveguide.

12. RECEIVER.

a. General. The function of the receiver is to take the weak echoes from the antenna system, amplify them sufficiently, detect the pulse envelope, amplify the pulses, and feed them to the indicator. Since radar frequencies are high it is difficult to obtain sufficient amplification. Therefore the receiver function of the radar system

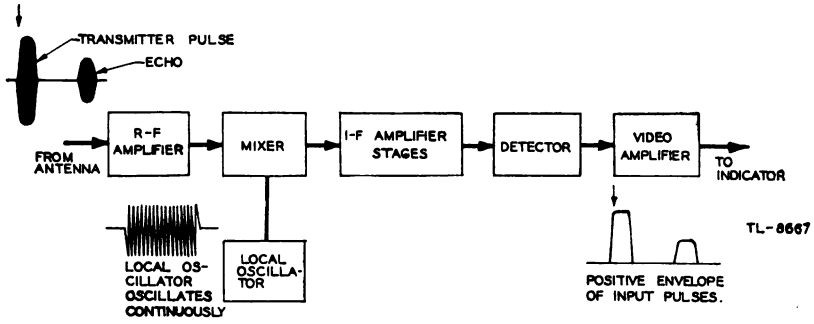

Figure 29. Components of radar receiver.

is performed by superheterodyne components of good stability and extreme sensitivity. The stability of operation is maintained in the microwave range of frequencies by careful design, and the over-all sensitivity of the receiver is greatly increased by the use of many intermediate-frequency stages. Special types of tubes having low interelectrode capacitances have also been developed for use in r-f, local-oscillator, and i-f stages.

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b. Components. (1) Figure 29 illustrates the receiver components of the radar system. The r-f amplifier may not be present in the higher frequency ranges and thus the received signal may be fed directly to the mixer. In this case it is desirable to use as short a receiver input transmission line as the design requirements allow. Thus the mixer and local oscillator may be located close to the T-junction of the transmission line in order that the received r-f energy may be converted to the lower intermediate frequency before being relayed to the remaining receiver components. One or two stages of i-f amplification are sometimes located immediately after the mixer-local oscillator stage, functioning as a preamplifier to offset the considerable attenuation encountered in coupling the very weak received signal to the remote receiver components.

(2) The components of the radar receiver may be distributed throughout the system in such a manner that their physical identity becomes lost. Figure 30 illustrates one representative distribution of the radar receiver components which makes it possible to locate the frequency-conversion portion in the immediate vicinity of the antenna and the video-amplifier portion in the vicinity of the indicator.

13. INDICATOR.

a. General. The indicator uses the received signals to produce a visual indication of the desired information. The cathode-ray oscilloscope is an ideal instrument for the presentation of radar data since it not only shows a variation of a single quantity such as voltage, but gives an indication of the relative values of two or more synchronized variations. The usual indicator is basically the same in function as the low-frequency test oscilloscope. The focusing, intensity, and positioning controls are similar. The sweep frequency of the radar indicator is determined by the pulse-repetition frequency of the system and the sweep duration is established by the setting of the range-selector switch.

b. Types of cathode-ray oscilloscopes used. (1) The simpler systems of data presentation generally use the electrostatic cathode-ray tube in which the electron beam is made to follow some pattern by controlled differences in potential between pairs of deflecting plates.

(2) The more highly refined systems of data presentation generally utilize the electromagnetic cathode-ray tube with a long-persistence screen. The position of the electron beam at any instant is determined by causing it to pass through a magnetic field produced by controlled currents through deflecting coils mounted outside the tube. If intensity modulation is used, the bias is such that the tube is held just beyond cut-off, and the video output of the receiver is applied to either

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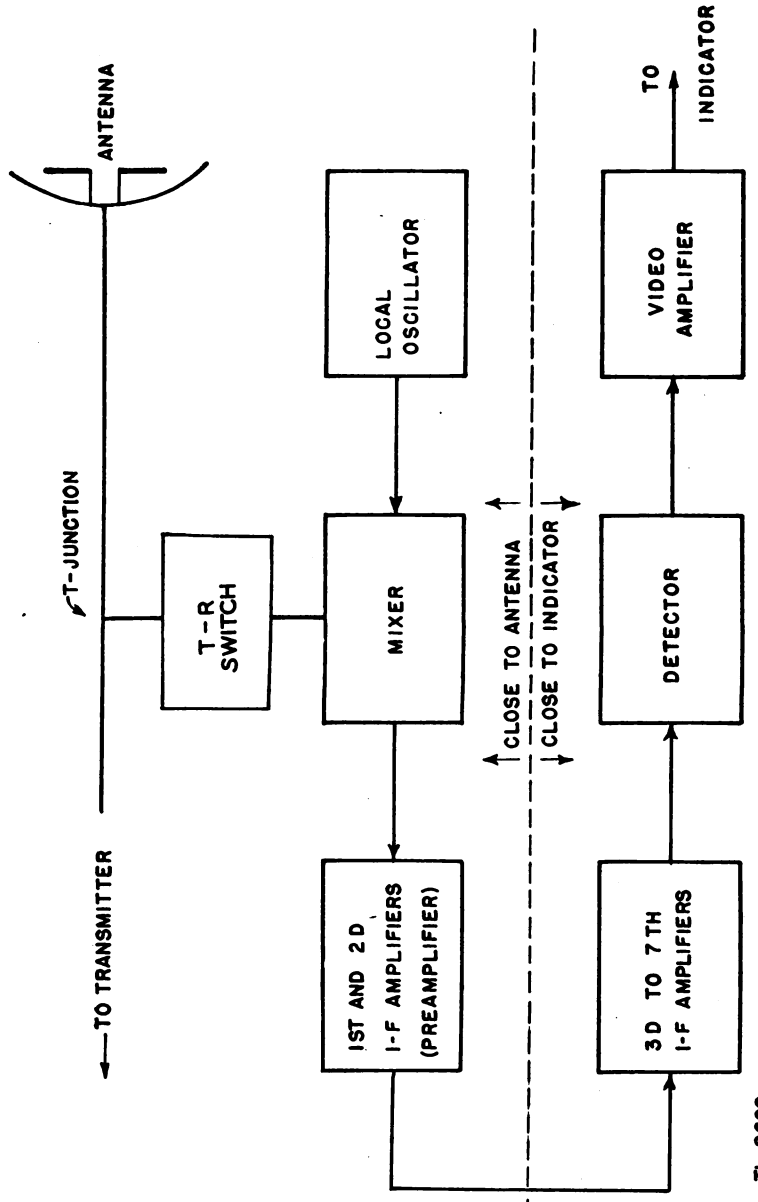

Figure 30. Possible distribution of receiver components.

the grid or cathode with such polarity as to release the beam and allow the trace to appear on the screen. Thus the bright spots on the screen represent returning echoes detected by the radar receiver.

c. Type A-scan presentation. (1) The A-scan (fig. 31) uses an electrostatic cathode-ray tube with a linear sweep applied to

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the horizontal deflecting plates to establish a time base, and with the video output of the receiver applied to the vertical deflecting plates. Since the sweep is linear with time, a scale which is calibrated in range may be placed on the oscilloscope screen. This scale permits the reading of range directly.

(2) Since the antenna beam is highly directive, the maximum received echo appears when the antenna is pointing directly at the

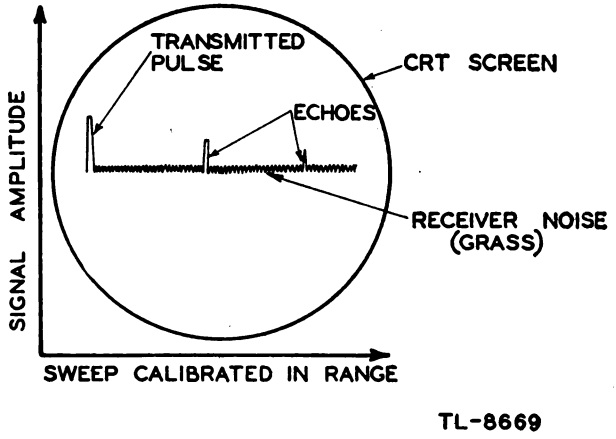

Figure 31. Type A-scan presentation.

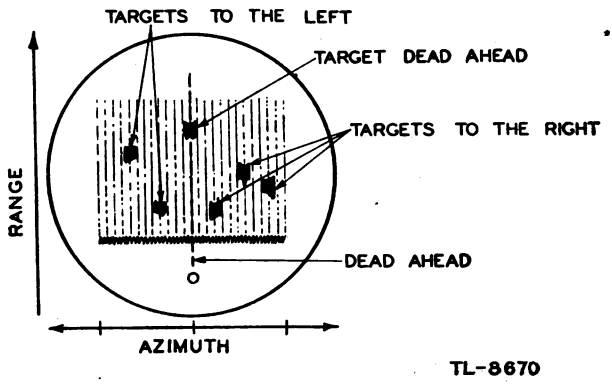

Figure 32. Type B-scan presentation.

target. Thus, by rotating the antenna until the echo pulse produces maximum deflections on the screen, an indication of direction in azimuth or elevation can be obtained.

d. Type B-scan presentation. The B-scan (fig. 32) plots range against azimuth. Usually an electromagnetic tube is used. The sweep current flows through the vertical deflecting coils. A positioning current controlled by the antenna position flows through the horizontal deflecting coils, so that the position of the vertical sweep

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is aligned with the position in azimuth of the antenna, which may scan a region up to 90° on either side of dead ahead. The return signals are used with an intensity-modulated scope to cause the target indications to appear on the screen.

e. Type C-scan presentation. The C-scan (fig. 33), developed primarily as a pilot's remote indicator, plots elevation against azimuth. The oscilloscope is intensity-modulated by the echo

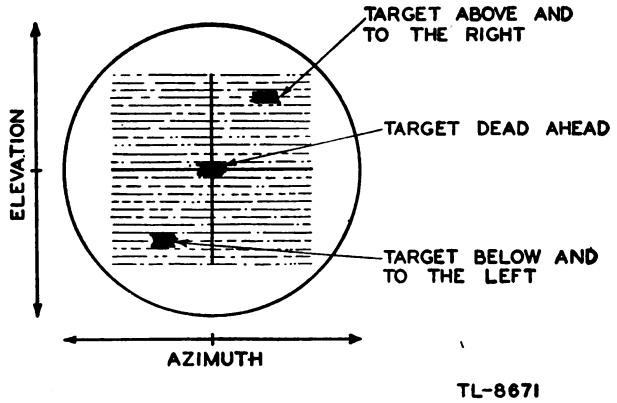

Figure 33. Type C-scan presentation.

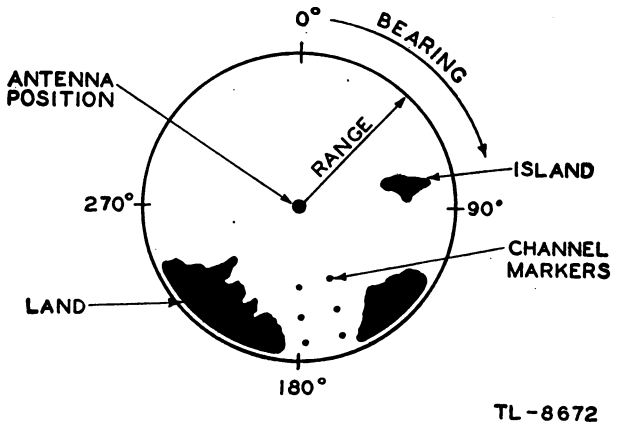

Figure 34. Type PPI-scan presentation.

signals. Modifications which present a means of estimating the range in addition to the indication of the elevation and bearing are more likely to be encountered than the basic type.

f. Type PPI-scan presentation. The PPI-scan (fig. 34) presents, in polar coordinates, a map of the area being covered with the antenna position occupying the center of the screen. The tube is intensity-modulated with the sweep moving from the center

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radially outward. The sweep position is controlled by and synchronized with the antenna position throughout 360° rotation. The top of the screen represents dead ahead; if the antenna is pointing dead ahead, the sweep moves from the center of the screen to the top. Likewise, if the antenna points 90° from dead ahead, the sweep moves from the center radially outward at an angle of 90° to the right of dead ahead. Thus, a polar map is developed on which the range is plotted radially against the position in azimuth, or bearing, through 360°. The PPI-scan finds considerable application in equipments designed for search, harbor control, convoy keeping, ground-controlled interception, and navigation.

g. Components. (1) The basic components of a radar indicator are a cathode-ray tube, a sweep circuit, and a gate circuit. These are illustrated in figure 35. Various refinements may be added

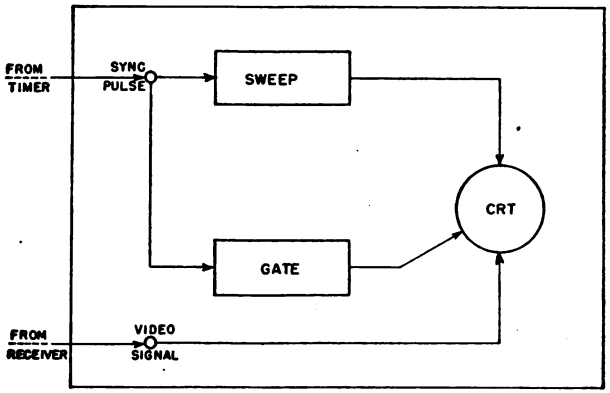

Figure 35. Basic components of radar indicator.

to improve the data presentation and to meet specific operational requirements.

(2) In order that the data supplied by the indicator may be useful, the indicator's performance must be synchronized with that of the other components of the system. Thus the start of the sweep must bear a definite time relation to the beginning of the transmitted pulse. The gating of the cathode-ray tube also must be timed with the sweep duration. Various methods of data presentation requiring sweep controls of varying degrees of complexity may be used.

14. POWER SUPPLY.

a. Distribution. In the functional diagram of the radar system (fig. 16), the power supply is represented as a single block. Functionally, this block is representative; however, it is unlikely that

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any *one* power supply could meet all the power requirements of a radar set. The distribution of the physical components of the system may be such as to make it impractical to lump the power-supply circuits into a single physical unit. Thus, different supplies are needed to meet the varying requirements of the system and must be designed accordingly. The power-supply *function* is performed, therefore, by various types of supplies distributed among the circuit components of the radar equipment.

b. Components. Figure 36 illustrates the power requirements of a typical microwave radar equipment. It shows a representative method of supplying the various components of any radar system with power.

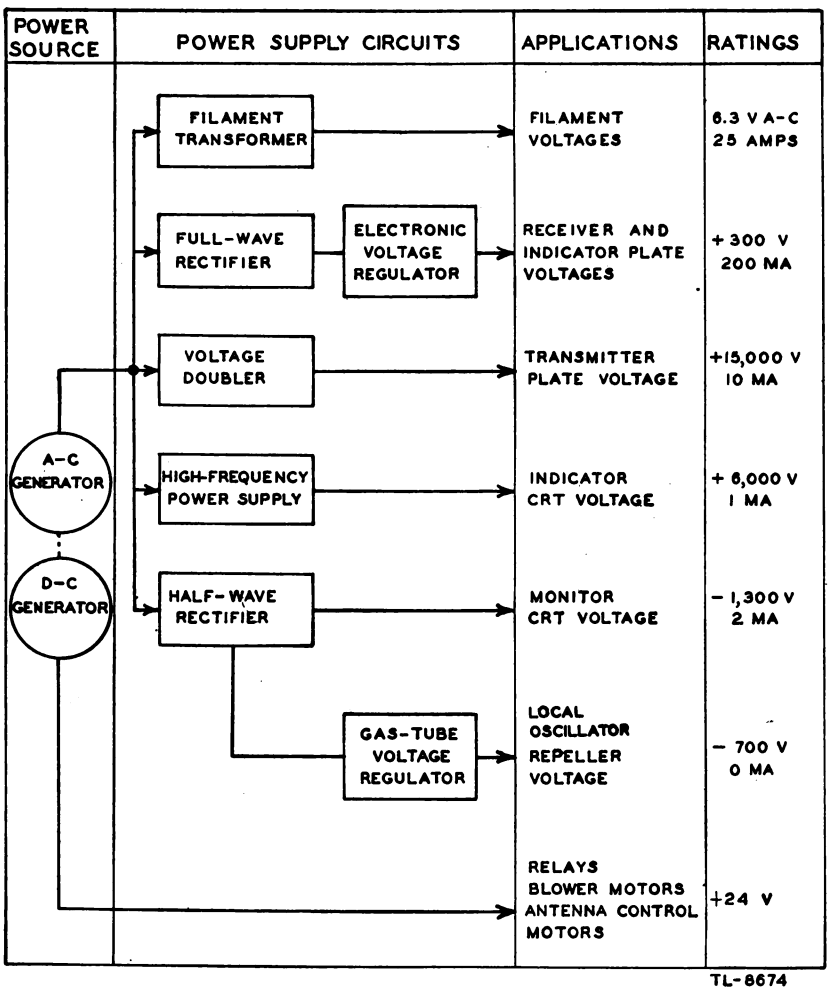

Figure 36. Power requirements for typical microwave equipment.

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Section III

Detailed Study of Self-Synchronized Long-Wave Radar System

15. GENERAL.

a. Purpose. The system to be studied in this section has been selected because it is a relatively simple system which nevertheless illustrates the fundamental principles and circuit applications used in radar. This self-synchronized radar system is intended for use in medium-range search for aircraft. It can be installed in fixed locations or on board ships. Because of the wavelength chosen for the carrier frequency, the set should be installed as high as possible above the surrounding terrain for effective operation against low-flying aircraft. The indicator permits measurement of range on both a 20,000-yard and 100,000-yard scale. The antenna is motor-driven to track targets in azimuth.

b. System constants. The carrier frequency selected is 100 megacycles per second, a relatively low frequency for radar. The pulse-repetition rate is approximately 500 pulses per second, but it may vary by plus or minus 100 pulses per second. The pulse width is nominally 5 microseconds. The useful peak power output from the transmitter is 15 kilowatts. The low power output limits the maximum range for detecting a single aircraft to about 50 miles.

c. System components. The components which comprise the system are shown in figure 37. The transmitter combines the functions of the timer and of the r-f generator into one set of circuit elements. The 5-microsecond r-f pulse is radiated by a stacked-dipole transmitting antenna. The returning echo signals are picked up by a similar receiving antenna. A superheterodyne receiver, with a sensitivity of about 1 microvolt, feeds its video output directly to the indicator. The timing pulse from the transmitter synchronizes the indicator sweep so that it repeats at the pulse-repetition frequency of the transmitter. The screen of the indicator is calibrated to read range directly. Necessary d-c voltages and the necessary heater voltages are provided by the power supply unit.

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16. TRANSMITTER.

a. General. Perhaps the simplest type of radar transmitter is the two-tube, tuned-grid, tuned-plate, self-pulsing triode oscillator shown in figure 38. No auxiliary modulation equipment is required with this transmitter because pulses of r-f energy are generated by the blocking action in the grid circuit. The rate at which the transmitter is pulsed is not absolutely constant, but the pulse-repetition tolerances

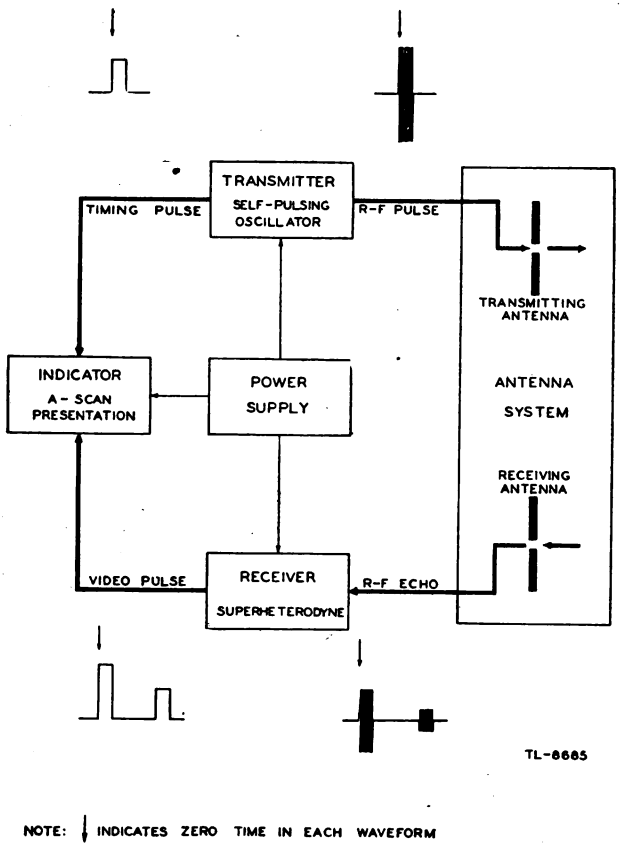

Figure 37. Self-synchronized radar set.

are broad because the action of the rest of the system depends on the timing pulse generated by the transmitter.

b. Tubes. (1) Since this transmitter is designed to operate at 100 megacycles, triode oscillator tubes can be satisfactorily used. At higher frequencies vacuum tubes are subject to limitations, such as those imposed by the transit time of the electrons, the inductance of the leads to the tube elements, and the interelectrode capacitances of the tube (sec. II). But moderately large transmitting triodes can

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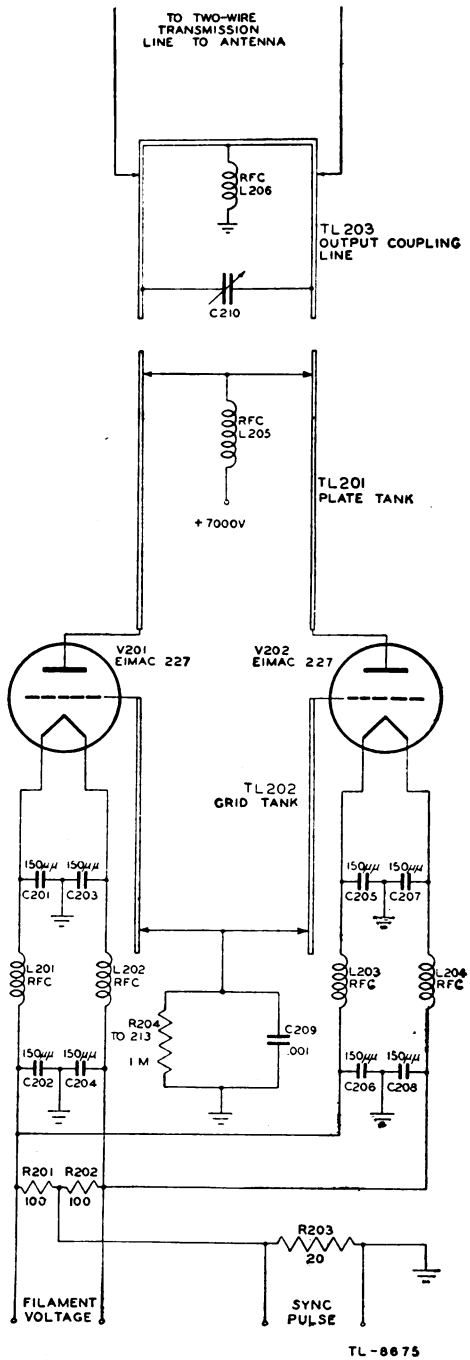

Figure 38. Self-pulsing transmitter circuit.

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be used at 100 megacycles because the inductance of the tube leads and the capacitance between elements can be used as part of the tuned circuit of the oscillator. For this reason, when the length of a quarter-wave Lecher-line tank circuit is measured, it must be remembered that the tube inductance and capacitance both tend to make the line shorter than a simple calculation would indicate.

(2) When the time required for an electron to go from cathode to plate (called the electron transit time) because an appreciable fraction of one cycle of the oscillation, the plate current gets out of phase with the grid voltage and the efficiency of the tube is lowered. The transit time may be reduced by making the tube dimensions smaller, so that the electrons do not have as far to travel, but this reduction in size limits the power output of the tube. Another way of reducing the transit time is to increase the speed of the electrons by using a greater plate voltage, so that the electrons travel a given distance in less time.

(3) When the plate voltage is increased above the rated value, the plate current also increases and many more electrons strike the plate. Most of the energy of the moving electrons is transformed into heat when they strike the plate; therefore, when the plate voltage is made greater, the energy dissipated at the plate must also be greater. If this increase is carried to an extreme, the plate will melt. However, the plate voltage on a triode used in a radar transmitter can be raised to a value three times greater than the rated voltage for continuous operation, because the tube is not in continuous use. Since the tube is idle most of the time, the plate has a long time in which to cool off. A very large current can be drawn from the tube for a few microseconds if the average power dissipated at the plate does not exceed the rated value for the tube.

(4) The transmitter for the radar system must generate a powerful r-f pulse. In order to do this, a very large current must flow through the tubes. The application of higher plate voltage can increase the output of a tube until the limit of filament emission is reached. Beyond this limit higher voltage cannot increase plate current, since all available electrons are already in use. The supply of electrons, however, can be increased by heating the filament to a higher temperature. The type 227 tube used in this radar system has a thoriated tungsten filament. The filament emission is increased by the use of a slightly higher filament voltage than is recommended by the manufacturer. Under these conditions a peak power output of 15 kilowatts is produced.

c. Tuned circuits. (1) At frequencies normally used for communications, oscillator-tuned circuits can be made with conventional inductors and capacitors. Ultra-high frequencies, however, require similar elements so small in size that it becomes extremely

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difficult to produce a usable tank circuit. In addition, the skin effect in the coils introduces resistance which reduces the Q of the oscillator. To avoid these defects, the tuned circuit for *u-h-f* oscillator is usually made of a quarter wavelength transmission line, sometimes called a Lecher line. A quarter-wave transmission line shorted at the far end acts like a parallel resonant circuit (sec. X, TM 11–466 and Navships 900,016). The Q of such a tuned circuit can be made large because the inductance and capacitance are distributed and because the skin effect can be minimized by using large-diameter, silver-plated rods for the quarter-wave line.

(2) The length of the quarter-wave line TL202 in the grid circuit is physically less than the length of the quarter-wave line in the plate circuit, because the capacitance from grid to cathode is larger than the capacitance from plate to cathode. The larger capacitance causes more of the tuned line to be effectively inside the tube envelope, so

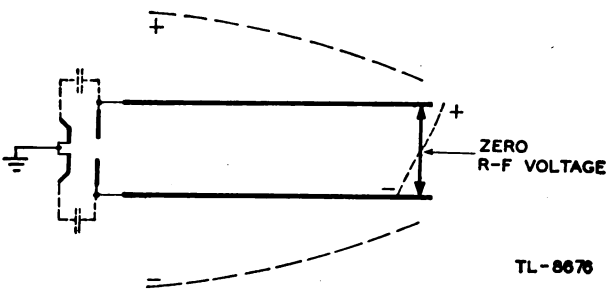

Figure 39. Standing wave of voltage across shorting bar.

that the grid line is shorter physically, although the electrical length of both lines is very nearly a quarter-wave.

(3) The operation of the tuned-grid, tuned-plate, push-pull oscillator is discussed in section V, TM 11–466 and Navships 900,016. Oscillations are generated in this transmitter in exactly the same manner as in a conventional tuned-grid, tuned-plate oscillator.

(4) When the tuned circuit of an oscillator is a Lecher line, it is simplest to connect the high voltage supply to the sliding short-circuit bar across the lines. Theoretically, the shorting bar has zero r-f voltage to ground. Actually, because of its physical length, there is a small part of the standing wave of voltage across it (fig. 39). The true neutral point is determined by the capacitance to ground of each plate, which changes slightly for different tubes. Changing the position of the supply voltage connection is avoided by using an r-f choke L205 (fig. 38) to prevent feedback of any r-f voltage into the power supply. The r-f ground is then established within the tubes by their interelectrode capacitances.

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d. Cathode filters. The timing pulse for the indicator in this system is produced across resistor R203 within the transmitter (fig. 38). This resistor, along with R201 and R202, forms an impedance to the radio-frequency current thus causing a degenerative voltage in the cathode circuit. The degenerative voltage reduces the regenerative feedback and therefore reduces the power output of the transmitter. The reduction can be partially avoided by the use of bypass capacitor at the tube sockets to provide low-impedance paths to ground for the r-f current. Since the filament leads of the type 227 tube are approximately 2 inches long, the actual filament r-f voltage cannot be reduced to zero. The impedance of the bypass capacitors is sufficiently low at radio frequencies, however, to increase greatly the amplitude of oscillation and, therefore, to increase the power output, without disturbing the pulse-forming network. In addition, C201 and C202, together with L201, form a filter which prevents the pulse of r-f voltage from feeding back into the power line through the filament transformer. This filter helps to reduce interference with other equipment by preventing the r-f disturbance from getting on the power line.

e. Method of coupling. (1) Energy is coupled out of the plate tank circuit TL201 by the tuned line TL203. The magnetic field that is set up by the r-f current in TL201 induces an r-f voltage in TL203. Thus, TL203 is in effect the tuned secondary of a transformer of which TL201 is the tuned primary.

(2) The shorting bar of the coupling line, TL203, is placed directly above the shorting bar of the plate-tuned line. The degree of coupling between the two tuned lines can be varied by raising or lowering TL203. In order that TL203 may be adjusted for maximum energy transfer, capacitor C210 is varied to make the line resonant at the transmitter frequency. The two-wire transmission line is connected to the coupling line at a point at which the impedance of the coupling line is equal to the impedance of the transmission line. If the match of impedance is very close, the energy transferred from TL203 to the transmission line is maximum.

(3) The r-f choke L206 is used to keep the coupling line, the transmission line, and the antenna at d-c ground potential. It prevents the accumulation of a static charge on any of these elements.

f. Pulsing action. (1) The r-f voltage generated in the plate tank circuit TL201 is modulated by the blocking action in the grid circuit of V201 and V202. This action is explained in section VII, TM 11–466, and Navships 900,016.

(2) The duration of the pulse of r-f energy is determined by the time required to charge capacitor C209 in the grid circuit. The capacitor is charged by the electrons which are attracted to the grids

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of the tubes when the r-f voltage in the grid tank circuit TL202 swings them positive. Therefore, the time required to charge C209 is affected by any of the factors which determine the magnitude of the r-f grid voltage. These are: the tuning of TL202 relative to the tuning of TL201, the magnitude of the d-c plate voltage applied to the tubes, the tuning of the capacitor C210 in the coupling line, the position of the transmission-line taps on TL203, and the degree of coupling between TL203 and TL201. When the transmitter is tuned for maximum power output, the duration of the transmitted pulse is controlled only by the size of C209. This size is selected to give a pulse length of approximately 5 microseconds.

(3) The pulse-repetition frequency of the oscillator can be varied by most of the adjustments that control the pulse length, since changing any one of them causes C209 to be charged to a slightly different voltage, and it therefore takes a different time for C209 to discharge to the voltage at which the tubes can again begin to conduct. The

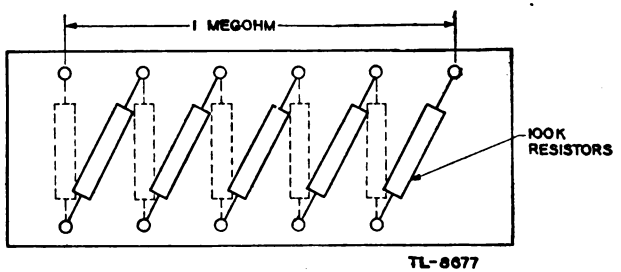

Figure 40. Terminal board for mounting grid resistors.

most practical adjustment for controlling the pulse-repetition frequency is to short out one or more of the 100,000-ohm resistors in the chain from R204 to R213. These resistors are mounted on a board as shown in figure 40. The pulse-repetition frequency is nominally 500 pulses per second, but this rate may be varied easily by any of the adjustments mentioned.

g. Timing pulse. (1) When the tubes V201 and V202 are conducting, during the pulse time, a large current flows in the plate circuit. In order to synchronize the indicator, the plate current is used to generate a pulse across R203.

(2) Since the negative side of the plate-voltage power supply is grounded, the electrons which make up the plate current flow from ground up through R203. The resistors R201 and R202 are used in order to divide the current equally between the two filament lines. The electrons flow through R203 and then divide, first between the two filament lines, and then alternately between the two tubes, since V201 and V202 conduct alternately. Most of the electrons which flow to V201 pass from the cathode of this tube to the plate, then out through

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half of TL201 and through L205 to the positive side of the plate power supply. From there they are returned to ground to complete the circuit. A few of the electrons which leave the cathode flow into the grid circuit to charge C209. The conduction through V202 is exactly the same as that in V201, except that V201 conducts only when V202 does not, since the tubes are in push-pull. The current through R203 never drops to zero during the pulse because of the alternate conduction of V201 and V202 and the filtering action in the filament lines.

(3) Since electrons flow from negative to positive, the upper end of R203 must be positive. There is a voltage across R203 only during the r-f pulse. This voltage rises at the beginning of the pulse and falls at the end, so that a positive pulse of voltage, which occurs at the same time as the r-f pulse, is generated across R203. The amplitude of the pulse across R203 is approximately 120 volts. This pulse is used to synchronize the generation of the sweep in the indicator.

17. ANTENNA SYSTEM.

a. General. (1) The functions of the antenna system are to radiate the r-f energy supplied by the transmitter, to convert the energy of any received electromagnetic field into a voltage, and to feed this voltage to the receiver. To perform these functions efficiently, the antenna must be properly designed for the frequency at which it is operated, and the impedances of the system feeding energy to the antenna must be properly matched.

(2) The two separate antennas used in this radar system must be arranged so that the high-power electromagnetic field which is radiated from the transmitting antenna does not induce a high voltage in the receiving antenna. To minimize coupling between the antennas, the receiving antenna is placed below the transmitting antenna.

(3) Antennas for use with radar systems are subject to many requirements, some of which are in direct conflict. The weight of an antenna must be as small as possible so that it may be installed and transported with ease. The structure must be strong to withstand the vibration and shock to which it may be subjected by shelling and bombing. The antenna structure must be designed to have as much open space as possible, so that it will offer minimum resistance to the wind. The antenna should be simple, mechanically reliable, and able to operate over a wide frequency band because usually its location is inaccessible for adjustment or repair. It must be directional and rotatable, in order that accurate bearings of targets may be obtained. All of these requirements are incorporated in the design of the antenna. It is not necessary to consider them in the field except in the rare cases where a temporary antenna may have to be erected after the original antenna has been shot away.

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b. Feed system. (1) The feed system of the transmitting antenna is shown schematically in figure 41. A coaxial-type line is used to eliminate possible radiation, and thus to prevent stray pickup of r-f energy by the receiver and indicator. The output coupling circuit in the transmitter is tuned to the frequency of the transmitter by adjustment of capacitor *C*. When this line is properly tuned, a standing wave exists on it, and the impedance between the two wires varies from zero at the short circuit to a high impedance at the open end. The sliding connections *A* and *B* may be adjusted to a point at which the impedance between them is 70 ohms, which is the characteristic impedance of the particular transmission line used. Under this condition, the energy transfer from the transmitter to the coaxial line is maximum. The open-wire line from the points *A* and *B* to the coaxial line is very short, and has only a small effect on the impedance that is seen looking from the output coupling into the coaxial line.

(2) The line balance converter, or bazooka as it is more commonly called, is used to prevent the r-f energy from appearing on the outside of the coaxial line. It does not assist in matching impedances. The outer conductor of the coaxial line is grounded, while both sides of the open-wire line should be above-ground potential. The bazooka acts as a choke or high impedance to prevent the grounding of the connection between the outer conductor of the coaxial line and the open-wire line.

(3) A rotating joint is necessary to allow the antenna to turn continuously. Since the coaxial line must go through the center of the pedestal on which the antenna is mounted, the rotating joint is generally built into the pedestal assembly. When two coaxial lines lead to the antenna, as in the case of this radar system, one of the lines which form the joint is constructed inside the other. The center conductor of one coaxial line is a hollow tube, as shown by *B* in figure 42. A third conductor is put inside the center conductor to form the second coaxial line, which will not interfere with the first because the r-f energy travels only in a very thin skin on the copper tube. Therefore, two entirely different r-f signals may be conducted by one copper tube: one signal on the inside skin and one on the outside skin.

(4) In order to use the signal from the inner transmission line, the method shown in figure 42 is used. The r-f energy of signal S_1 is conducted on the inside surface of conductor *A* and the outside surface of conductor *B*. The r-f energy of signal S_2 is conducted on the inside surface of conductor *B* and the outside surface of conductor *C*. At the point where it is desired to lead out the signal S_2, conductors *B* and *C* are brought out. However, since signal S_1 is on the outside of conductor *B*, it is necessary to extend conductor *A* a quarter-wave-

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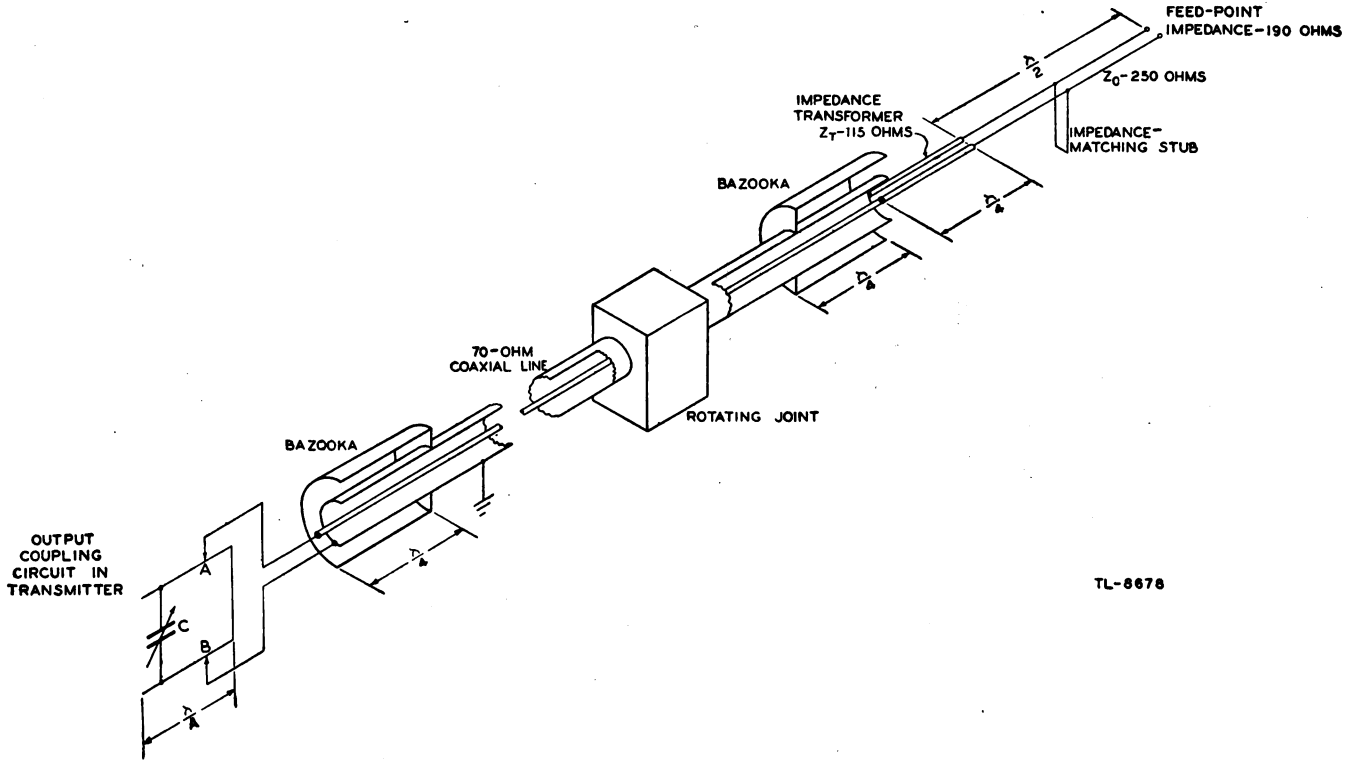

Figure 41. Transmission system between transmitter and transmitting antenna.

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length along the side connection, and to short A to B at this point to prevent signal S_1 from being radiated from the outside of conductor B.

(5) The rotating joint is made by enlarging one end of each conductor so that it telescopes over the end of its mate as shown at D. The enlargement is slit lengthwise into many fingers, and the metal is specially treated to make it springy in order to insure a good wiping contact.

(6) The characteristic impedance of the coaxial transmission line is 70 ohms. The impedance of the antenna is approximately 190 ohms at the feed point. In order to make an approximate match of im-

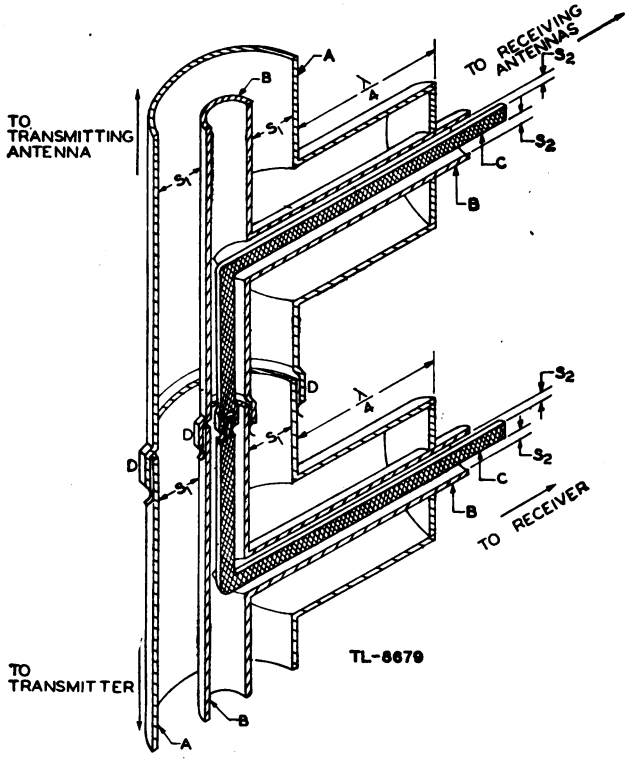

Figure 42. Rotating joint for double coaxial line.

pedance between the coaxial line and the antenna, the impedance transformer is used (fig. 41). This transformer is a quarter-wavelength section of two-wire line whose characteristic impedance is determined by the two impedances between which it is located. In this case, the characteristic impedance of the transformer is:

$$Z_t = \sqrt{70 \times 190} = 115 \text{ ohms.}$$

(7) In order to reduce the standing waves on the line to a minimum, a closer match of impedance is necessary than is usually possible with

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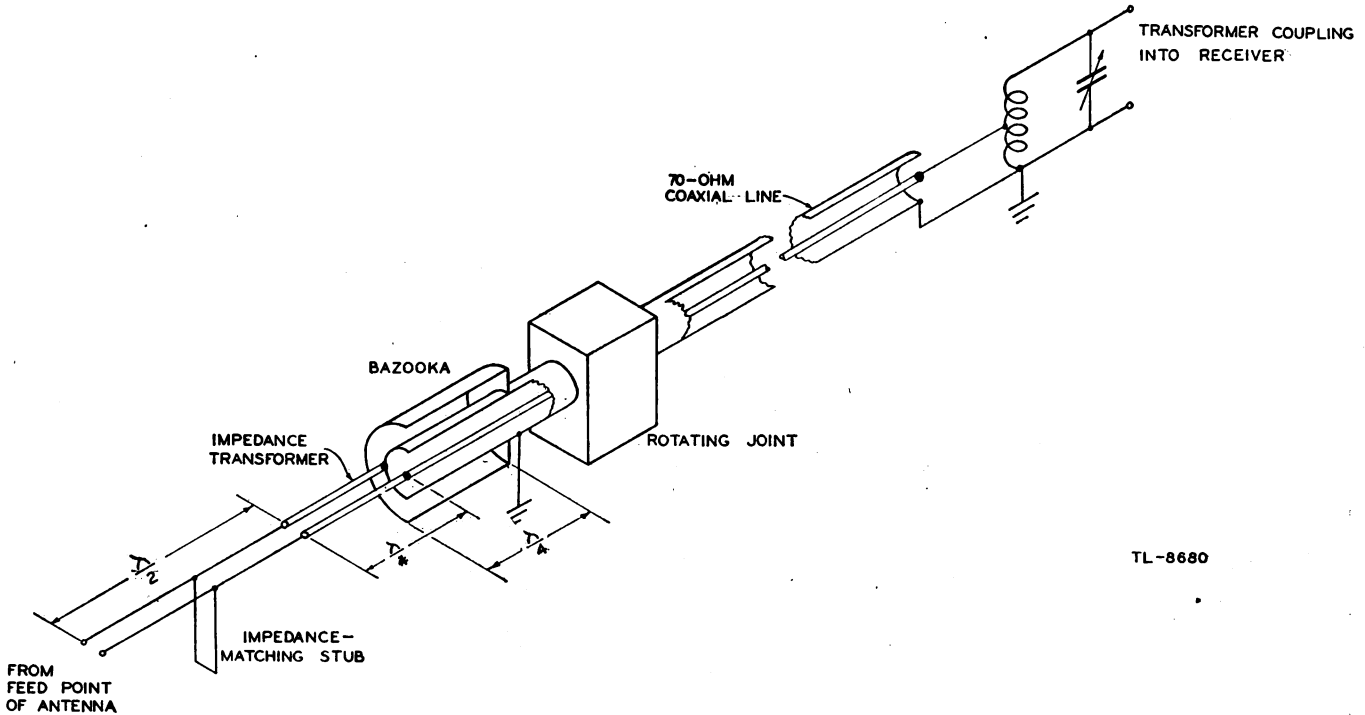

Figure 43. Transmission system between receiving antenna and receiver.

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the impedance transformer. The impedance-matching stub is therefore used to correct the remaining mismatch of impedance. Its length and position on the line is critical, and once established it should not be moved. The adjustment is made at the factory, where elaborate test equipment is available. By the use of this equipment both the length and the position of the stub may be set for minimum standing waves on the transmission line.

(8) The transmission line which connects the receiving antenna to the receiver is shown schematically in figure 43. It is similar to the line to the transmitting antenna, except for the termination at the receiver. Since one side of the input transformer is grounded, no

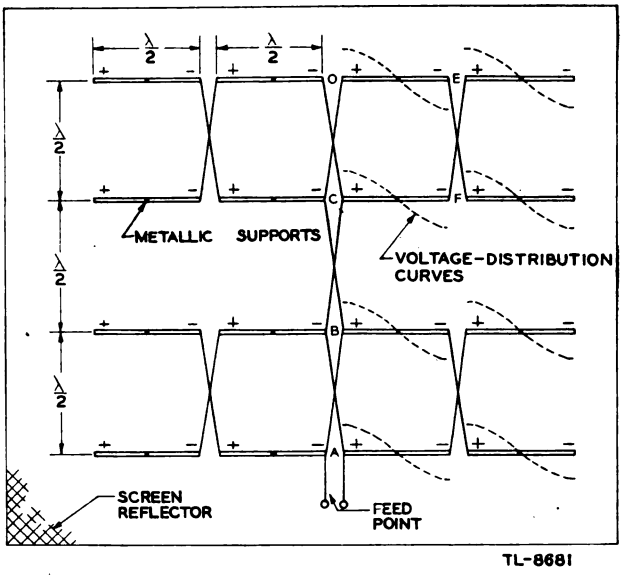

Figure 44. Transmitting or receiving antenna.

bazooka is needed at the receiver end. The auto-transformer is designed so that the impedance presented across the terminals of the coaxial line is 70 ohms.

c. Antenna arrays. (1) The transmitting and receiving antennas, which are identical, are composed of arrays of stacked half-wave elements as shown in figure 25. Because the frequency of this radar system is 100 megacycles, the antenna must be made large in order to obtain the desired directivity. One section of the system is shown in figure 44.

(2) All of the dipoles are fed in phase. If at some instant the voltage on the right-hand element at point *A* is at a positive maximum, the voltage on the left-hand element at this point is at a negative maximum. The transmission line between points *A* and *B* is a half-wave

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long, and the wires are transposed as shown. The voltage at one end of a half-wave line is 180° out of phase with that at the other end. Therefore the voltage on the right-hand element at point *B* is at a positive maximum and that on the left-hand element is a negative maximum. For the instant chosen, the polarity of the voltage is shown on all elements. The voltage distribution on half of the elements is shown by the dotted curves.

(3) Each individual radiating element has a point of null, or zero r-f voltage, approximately at its center. A connection between the center point and ground (the screen reflector) can be established without causing a current flow because the voltage is zero. This fact permits the use of a metal supporting rod from screen to radiating element. The rod may be welded for strength to the screen and radiating element. The rod holds the radiating element approximately one-eighth wavelength in front of the screen.

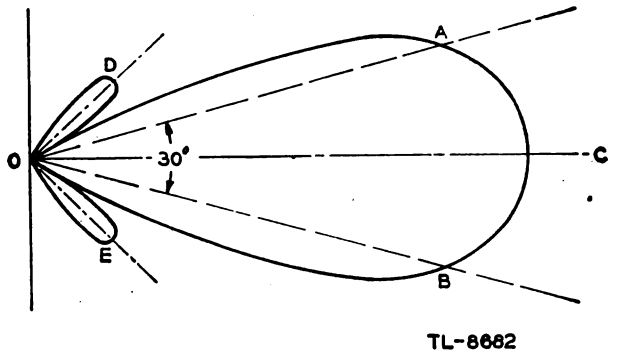

Figure 45. Radiation pattern in horizontal plane.

(4) The reflector is a metal screen mounted on a suitably strong framework. A screen is used to minimize the wind resistance. A plate with no holes in it would be a more effective reflector than the screen, but it would have tremendous forces exerted on it by the wind. If the holes in the screen are not too large, it will be almost as effective as the plate in reflecting the energy radiated by the antenna.

(5) The feed impedance of one pair of half-way elements mounted one-eighth wavelength in front of a screen is approximately 2,000 ohms. The null on the radiator is a single point, but for mechanical strength the supporting rods must be of fairly large diameter. A small current is drawn by each supporting rod. The impedances of these rods are in parallel with the impedance of the feed point, which is therefore reduced to approximately 1,500 ohms. There are 16 half-wave elements in the antenna, which may be considered as eight dipoles effectively in parallel. The net impedance of the whole array there-

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fore is: 1500/8=188 ohms. This value of feed impedance is approximate only; it is just as correct to round off the figure to 190 ohms.

(6) The pattern of this antenna in the horizontal plane is shown in figure 45. Maximum signal is radiated along the line *OC*. The size of the echo received from an object which lies along *OC* is greater than the echo from any target of similar size in any other direction. The signal radiated along either *OA* or *OB* is 70 percent of the maximum signal. Since the signal is measured by the voltage which it can induce in the receiving antenna, the 70-percent signal corresponds to one-half of the maximum received power. The points *A* and *B* are therefore called the *half-power points*. The width of the beam is given by stating the size of the angle *AOB*, the angle at half power, which is about 30° in this antenna. The beam angle is generally used to describe the directivity of the antenna.

(7) The two small lobes of energy at *D* and *E* are called secondary lobes. They are described by stating the angle *DOC* and by measuring the length of the line *OD* as a percentage of the length of *OC*. These secondary lobes are usually symmetrical about the axis *OC* of the radiated energy. At short ranges, echoes can be obtained from the energy radiated in the secondary lobes. These echoes are very confusing if there are many targets close together, as in a convoy. To prevent this confusion, antennas for radar systems which are to be used for convoy keeping or similar work must be designed to minimize the effect of secondary lobes.

(8) The sketches in figures 46 and 47 show approximately how this antenna looks when erected and ready for use. Note that the reflecting screen is relatively large. If a single antenna were used, the structure could be half as large. If the frequency were higher, an antenna of this size could be much more directive, or equal directivity could be obtained with a smaller antenna.

d. Rotating mechanism. (1) Every radar system must have some means of pointing its radiated energy in any desired direction. Practically all radar systems accomplish this by rotating the antenna.

(2) The method employed in the system under discussion is a simple motor drive which can be controlled in direction and rate of rotation. The position of the antenna mount in azimuth is indicated by a scale around the base of the tower. A mechanical gear train can be employed to transmit the data to the operating position.

18. RECEIVER.

a. General. (1) The effective range of a radar system depends on its ability to distinguish between the echo returned by a target and other disturbances which may be present. Although the total

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radiated power may be many kilowatts, only a part reaches the target and a still smaller amount is returned to the receiving system. The available signal from the most distant targets may be approximately 1 microvolt or less. The receiver must be capable of amplifying this very weak echo signal, so that it can be used to control the electron

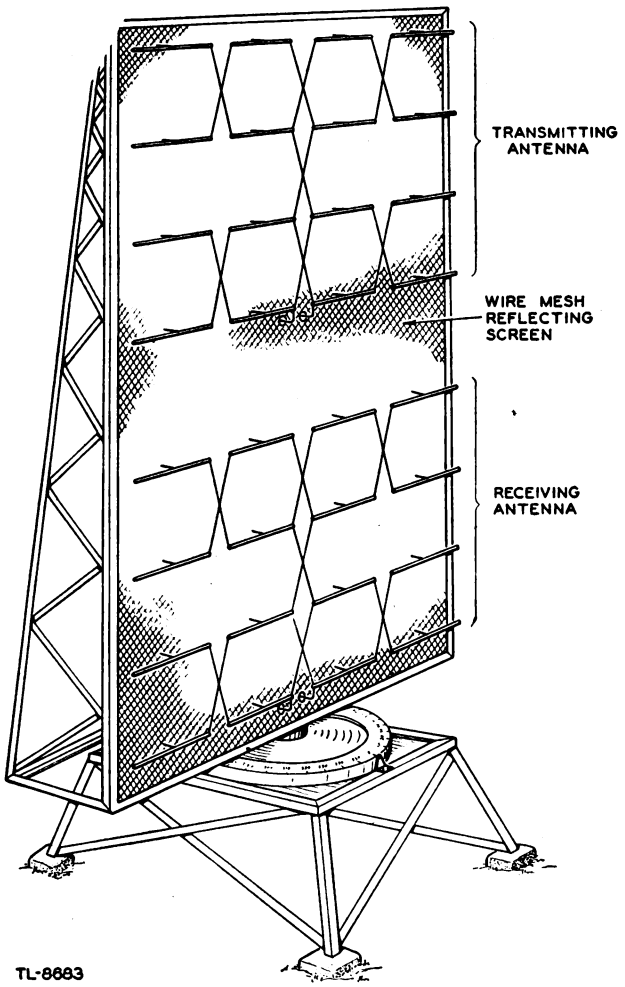

Figure 46. Sketch of antenna system (front view).

beam of a cathode-ray tube. Basically, the receiver is an amplifier in which vacuum tubes are used to increase the amplitude of a very small voltage.

(2) An amplifier tube uses a signal on its grid to control the flow of plate current through an external load. The gain obtained depends on the ability of the tube to control current and on the size of the

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plate load across which the increased signal voltage appears. To obtain maximum gain a tube with high transconductance is used with a plate-load impedance as high as practicable.

(3) The value of the plate-load impedance for all radar frequencies is primarily determined by the carrier frequency of the received signal. Since the pulse consists of the carrier and side bands which

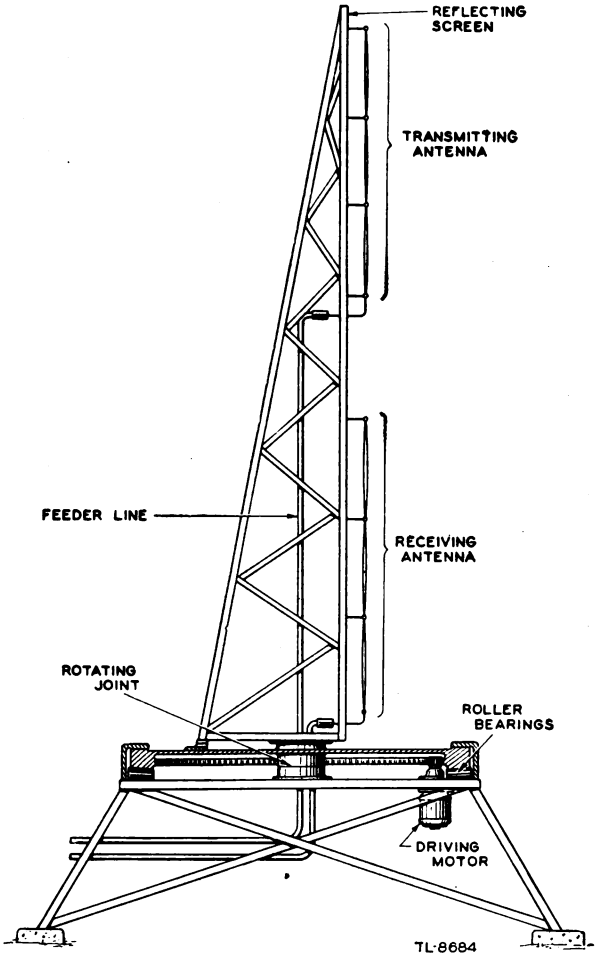

Figure 47. Sketch of antenna system (side view).

occupy a relatively small portion of the r-f spectrum, a tuned circuit is normally used. This circuit consists of an inductance effectively in parallel with the tube input and output capacitances, distributed wiring capacitance, and any capacitance which may be added to tune the circuit to resonance (fig. 48). The smaller the capacitance used, the larger the inductance at a given frequency and the higher the plate-

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load impedance. As frequency is increased, the total capacitance is reduced by eliminating any added capacitance and by careful circuit construction and selection of tubes.

(4) If the amount of gain is to be maintained at higher frequencies, the tube used must have small interelectrode capacitances. The upper limit of frequency is reached when it is physically impossible to reduce further the interelectrode capacitances within the tube. Beyond this limit the gain decreases with increases in the carrier frequency. A point is soon reached where the gain per stage is so small that an impractical number of tubes is required to raise the weak signal to a usable voltage.

(5) It must be possible to distinguish the received echo from any other electrical disturbances present, most of which are produced within the receiving system. Since noise voltages are produced by the tubes and by circuit elements, the tubes and associated circuits must

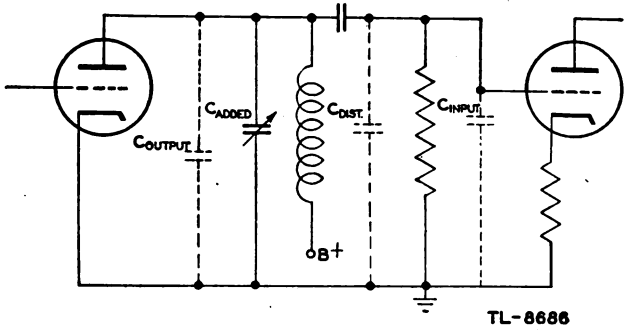

Figure 48. Tuned circuit of r-f amplifier.

be chosen from the standpoint of noise level as well as gain. The smallest signal to be received must equal or exceed the inherent noise voltage present in the first amplifier stage.

b. Superheterodyne receiver. (1) The superheterodyne receiver is used almost universally because it provides a higher over-all gain with fewer tubes than do other types of receivers. The heterodyne principle involves the conversion of the higher carrier frequency to an intermediate frequency at which the gain per stage can be made greater. The frequency conversion is accomplished by mixing, or beating, the received signal with a signal of different frequency generated in the receiver. The mixer stage produces an output voltage at a frequency which is the difference of the two signals applied. This difference signal is amplified by the intermediate-frequency (i-f) amplifier, and then is detected and amplified in the usual manner.

(2) A functional block diagram of the receiver used in this system, which is a typical radar receiver in many ways, is shown in figure 49.

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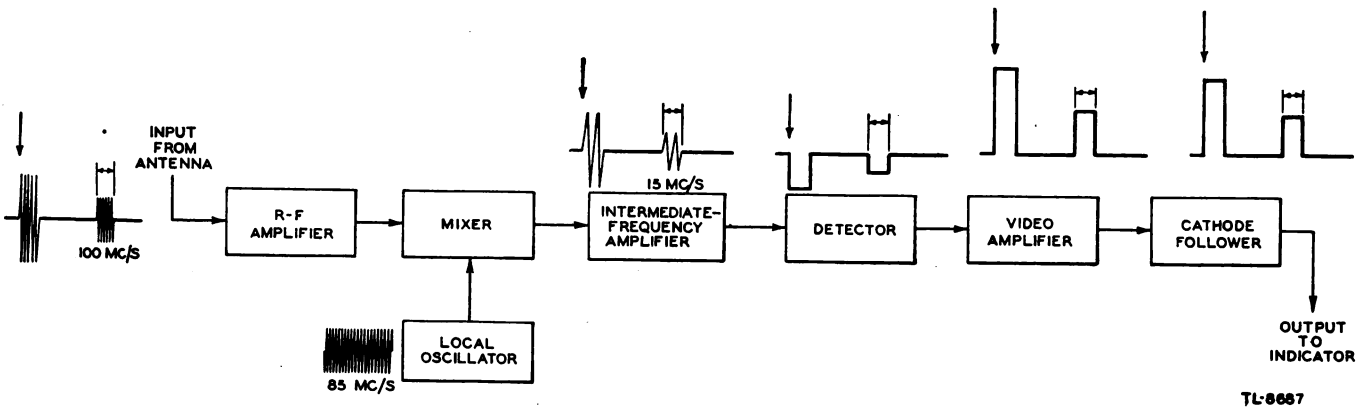

Figure 49. Functional diagram of superheterodyne radar receiver.

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For any given local-oscillator frequency there are two carrier frequencies which will produce the same intermediate frequency in the mixer output. It is desirable, therefore, to use a tuned r-f amplifier ahead of the mixer stage to discriminate against all but the desired carrier frequency. When the carrier frequency is so high that the r-f amplifier contributes more noise than gain, this stage is eliminated. At the carrier frequency used in this system, 100 megacycles per second, the r-f amplifier is included.

(3) The local oscillator generates a constant-amplitude signal of 85 megacycle which is mixed with the 100-megacycle input to produce a 15-megacycle intermediate frequency. The output of the mixer is amplified selectively to eliminate the 85- and 100-megacycle signal components which are present. In eliminating these components, the i-f amplifier must not distort the pulse shape of the received echo. A pulse with steep sides contains voltages of many frequencies, as explained in section III, TM 11–466 and Navships 900,016. When the pulse is applied to, or produced by, an r-f generator, the transmitted energy consists of the carrier and side bands. These side bands extend both above and below the carrier frequency by an amount determined by the frequency components of the pulse itself. The band width of the i-f amplifier must be great enough to pass the required side bands.

(4) After the echo amplitude has been increased to a reasonable value, the signal is passed through a detector to reproduce the r-f envelope as a video pulse. The video amplifier provides the signal output necessary to operate the indicator, reproducing the pulse shape as faithfully as possible. Whenever a low impedance load is to be placed across the terminals of the receiver, a cathode-follower tube is used as a low-impedance output stage to match the load.

c. R-f amplifier. (1) The receiver circuit diagram is shown in figure 50. The 100-megacycle echoes picked up by the receiving antenna are applied to the grid of the first r-f amplifier through an autotransformer L301. The input line is tapped down to provide a match for the 70-ohm coaxial line. The autotransformer is tuned to resonance by stray capacitance and the variable capacitor C301. A small voltage gain is realized by transformer action. V301 is a remote-cut-off acorn tube, type 956, designed to have high gain, low noise, and low interelectrode capacitance. Bias is provided by the cathode resistor R301, which is by-passed by capacitor C303 to avoid degeneration. A filter network, composed of L303, R302, R303, C302, and C304, is used to prevent r-f energy on the plate and screen grid from reaching the power supply, while supplying the necessary d-c voltages. The capacitors C302 and C304 are connected to cathode to insure a very short path for the r-f current to return to the tube.

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(2) The plate load for the first r-f amplifier is a transformer, L302 and L304, whose secondary is tuned by capacitor C306. The gain of the type 956 tube is about 5 at 100 megacycles. The coupling between the windings of the transformer is aided by capacitor C305 in order to obtain a wider bandwidth. The second r-f tube has its grid tapped down on the secondary to decrease the effect of the input capacitance of the tube. Bias, screen grid, and plate voltages are obtained in a similar manner to that used on the first r-f stage.

(3) The coupling circuit betwen the second r-f tube and the mixer is a tuned circuit consisting of resistor R306, inductor L310, capacitor C315, and distributed capacitance. Capacitor C310 blocks the d-c voltage from tube V304. Resistor R306 broadens the response of the tuned circuit. A higher supply voltage is used on the second r-f amplifier than on the first to compensate for the voltage drop across resistor R306.

d. Local oscillator. (1) The source of the beating signal is a triode tube V303, a type 955 acorn, connected in a modified Hartley circuit. The requirements for the local oscillator are that it should be stable in frequency and should furnish a sufficient signal to provide reliable mixer operation.

(2) The oscillator circuit may be considered as a tuned amplifier in which part of the output is fed back into the input. The tuned circuit consists of the inductor L307, capacitor C312, the interelectrode capacitance of the tube, and distributed capacitance (fig. 51). The amount of feedback is determined by the size of capacitance C_{GK} compared to capacitance C_{PK}. Grid-leak bias is provided by resistor R308 and capacitor C311. The r-f signal generated is kept out of the power supply by the filter composed of R307, C313, and L309 (fig. 50).

(3) The beating signal is coupled into the mixer input circuit through a link coupling consisting of the inductors L308 and L311 and a low-impedance line between them. The coupling is just sufficient to furnish the required signal without loading the oscillator and shifting its frequency. Changes in frequency during the warm-up period of the oscillator are corrected by the LOCAL OSCILLATOR TUNING control, C312.

e. Mixer. A diode tube, V304, is used as a mixer for the local-oscillator output and the echo signals. The diode loads its input circuit during the time when the applied signals are positive. To reduce this effect, the diode plate is tapped down on the inductor L310. The output of the mixer tube is a current which includes components whose frequencies are those of the applied signals, their sum, and their difference, which is the desired intermediate frequency. This current is passed through the primary of a transformer T301 and induces a voltage in the secondary. The undesirable signals are elim-

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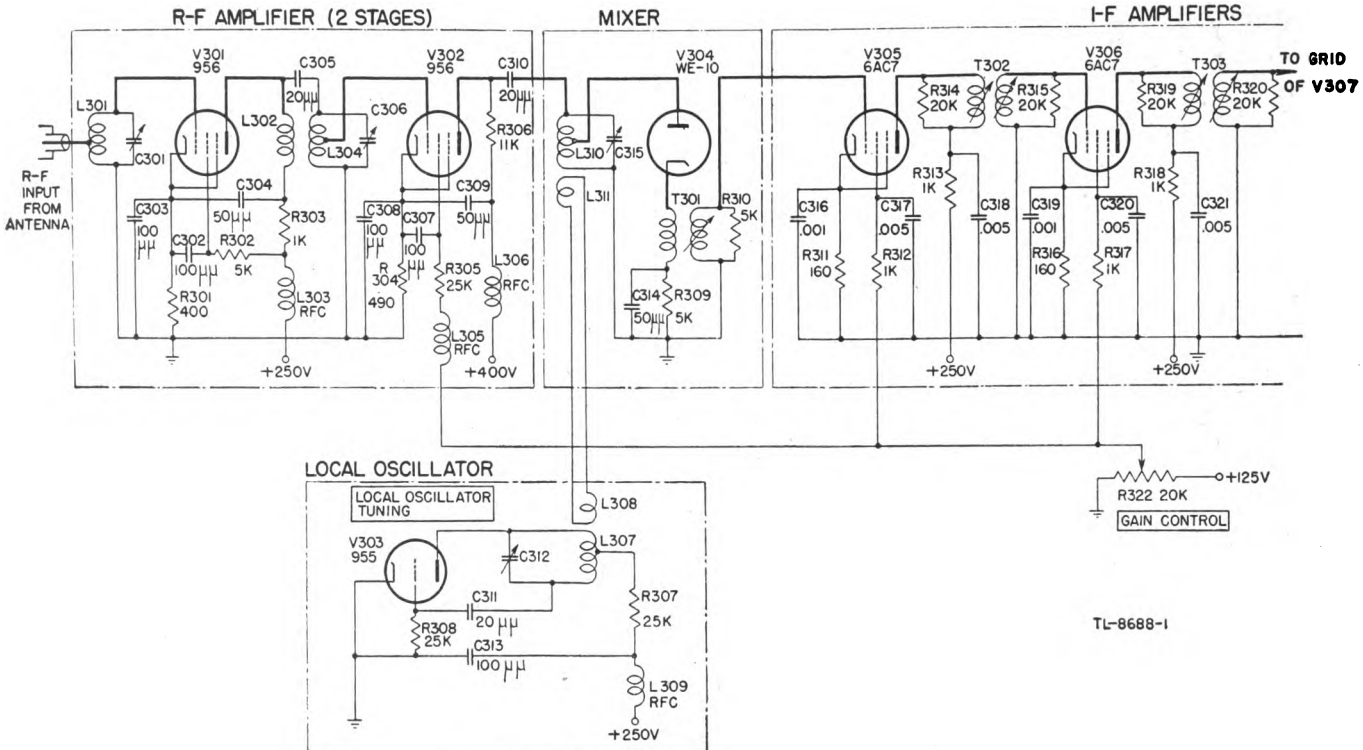

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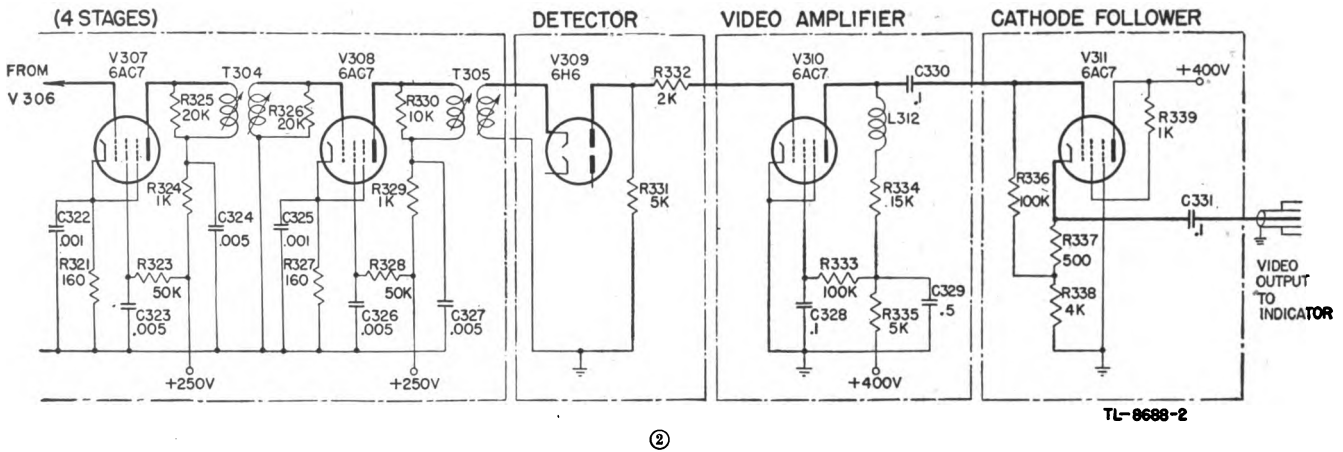

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Figure 50. Circuit diagram of superheterodyne radar receiver.

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inated by tuning the secondary to the intermediate frequency of 15 megacycles and building up only the i-f voltage across resistor R310. Resistor R309 and capacitor C314 provide a bias during individual pulses to prevent overloading.

f. I-f amplifier. (1) Four tubes, V305, V306, V307, and V308, are used to increase the amplitude of the i-f output of the mixer. The tube employed, the type 6AC7, is a high-transconductance pentode with low interelectrode capacitances. All four stages are similar in construction except for the screen voltage supply for the first two.

(2) The signal for each stage is taken from the secondary of the preceding coupling transformer and applied between grid of the amplifier tube and ground. The tube itself uses cathode bias from a bypassed resistor, and screen voltage which is supplied through a resistor-capacitor filter to reduce interstage coupling. The plate load is a transformer whose primary and secondary windings are tuned to the intermediate frequency by distributed and interelectrode capacitance. Exact tuning is provided by iron-dust slugs which act as

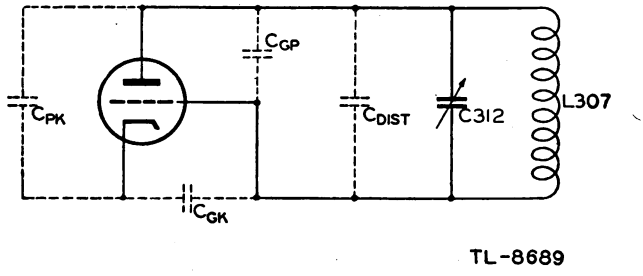

Figure 51. Equivalent local-oscillator circuit.

variable cores in the coils to change their inductance. Gain is sacrificed by resistance loading of each winding, in order to provide a 1-megacycle band-pass response, which preserves the pulse shape.

(3) The gain of the second r-f amplifier and the first two i-f amplifier stages are controlled together by means of the screen voltage. This system constitutes the entire gain control for the receiver. Potentiometer R322 provides the variable screen voltage, which can be adjusted from zero to 125 volts.

(4) The i-f amplifier is totally inclosed in a metal shield to decrease capacitative coupling with other parts of the receiver. This shielding prevents regeneration and possible oscillation.

g. Detector. The detector is a diode V309, using one half of a type 6H6 tube to rectify the i-f signal. The rectified current develops a negative pulse across the load resistor R331, which is directly coupled to the video amplifier. The i-f voltage is filtered from the pulse envelope by series resistor R332 and interelectrode capacitance of the video amplifier. There is a slight loss in a diode detector.

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h. Video amplifier. The video amplifier is used to raise the detected pulse voltage to the magnitude required to operate the indicator. Since the detector output is always negative in polarity, the video-amplifier tube V310 is operated without bias. The screen voltage is supplied through resistor R333, which acts both as a dropping resistor and as a filter. The plate load consists of resistor R334 and inductor L312 in series. The over-all load seen by the tube tends to increase with the frequency, and therefore increases the gain of the tube at the higher frequencies. This inductor corrects for the shunting effect of the output capacitance of tube V310 and the input capacitance of tube V311, which normally decrease the gain as frequency rises. The echo pulses therefore are amplified without change in waveform, except for the inversion, or change in polarity.

i. Cathode follower. The cathode-follower stage, tube V311, is used to couple the video signal to the indicator with a sufficiently good impedance match to minimize the distortion and loss of amplitude which would normally be encountered if a coaxial cable were used to feed the video signal to a remotely located indicator. No voltage inversion results from the use of the cathode follower. Only a slight loss is inserted in producing the impedance match between the high output impedance of the video amplifier and the low impedance of the coaxial cable.

19. INDICATOR.

a. General. (1) The function of the indicator is to measure the time required for the transmitting pulse to travel to the target and back and to apply this time to measure the distance between the target and the radar set. To perform this function the trace on the cathode-ray tube screen can be calibrated in terms of distance (sec. II). The spot on the tube is usually deflected by a saw-tooth waveform to produce a linear time base. Since zero time for each sweep is the instant when the transmitted pulse starts, the saw-tooth wave must be very carefully synchronized with the transmitted pulse.

(2) In order to prevent the appearance of the return trace on the screen of the scope, a gating pulse is applied to the cathode-ray tube. This gating pulse permits electrons to flow in the cathode-ray beam only during the time of the forward sweep of the saw-tooth wave. No electrons are permitted to strike the screen during the flyback or return-trace time. Because this pulse, in a sense, opens and shuts a gate through which the electrons in the cathode-ray tube must pass, it is sometimes called an *intensity-gate* voltage.

(3) Radar systems used for general searching must be capable of covering very long ranges, and therefore need a slow-speed sweep. As targets approach the radar station, more accurate data on their position is needed than is possible with the slow-speed sweep. To

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provide more accurate ranging on close targets, most radar systems are provided with several speeds of sweeps.

(4) The indicator used in this radar system is composed of the essential circuit components for producing a type A-scan presentation of data (fig. 52). The available ranges are 20,000 yards, shown by the solid-line waveforms, and 100,000 yards, shown by the broken-line waveforms. The timing pulse (fig. 52①) is limited to a fixed amplitude (fig. 52②) by diode V401. The sweep generator is timed by this pulse to produce an exponential rise of voltage in a fixed length of time. Since there are two ranges, two rates of rise can be selected (fig. 52③). The remainder of the circuits in the indicator convert the waveform of figure 52③ into that of figure 53⑤, the actual sweep voltage. Comparison of these waveforms shows that two changes must be made. First, the voltage rise for each sweep must be completed in the time corresponding to the range selected. The limiting of voltage rise is accomplished in the grid of the limiter-amplifier tube, V404 (fig. 52④). Second, the amplitudes of both sweeps must be equal and of the proper magnitude to cover the calibrated portion of the oscilloscope screen. The limiter-amplifier takes care of this problem (fig. 52⑤). Inverter tube V405 is used to produce the effect of a push-pull sweep by inverting the output of the limiter-amplifier (fig. 52⑥) and applying the result to the right horizontal deflecting plate. The limiter-amplifier output is applied directly to the left horizontal deflecting plate. The limiter-amplifier output is differentiated and applied to the indicator gate tube, V406. The output of this stage is a positive-going square wave (fig. 52⑦) which permits electrons to flow only during the sweep time.

b. Sweep generator. (1) The sweep generator uses a vacuum tube to control the charging and discharging of a capacitor. In the circuit shown in figure 53, the input timing pulse from the transmitter is applied to the sweep generator through a diode-limiter circuit, including tube V401. The pulse duration is approximately 5 microseconds and the magnitude is about 120 volts. The limiter is used to provide a fixed pulse amplitude of +38 volts to the sweep-generator tube V402. The limiter tube, V401, has its cathode raised to a potential of +38 volts above ground by the voltage divider, consisting of R402 and R403. As the input pulse rises to a potential more positive than 38 volts, V401 conducts. The current which flows in the diode also flows in R401. The voltage drop across R401 reduces the magnitude of the pulse applied to the grid of V402.

(2) The grid of tube V402 is normally held slightly positive with respect to cathode by a voltage divider, consisting of resistors R405 and R406. A change in the setting of resistor R406 has little effect on the grid potential because of grid current drawn through the

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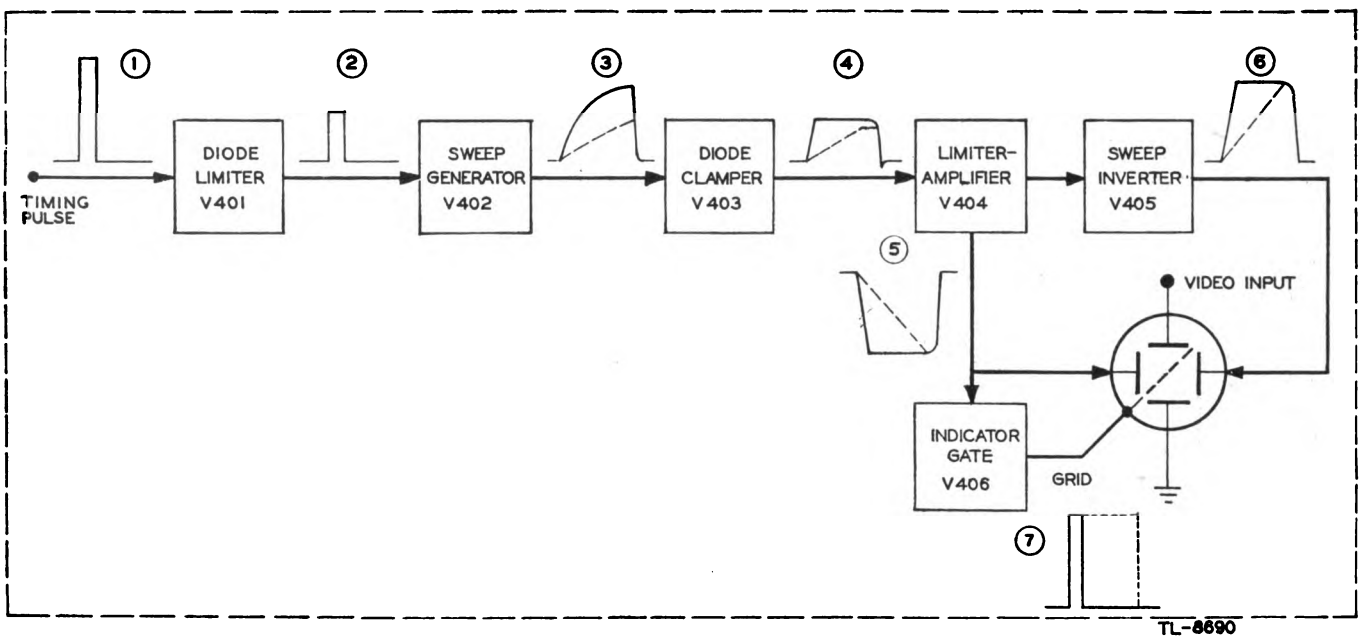

Figure 52. Indicator block diagram.

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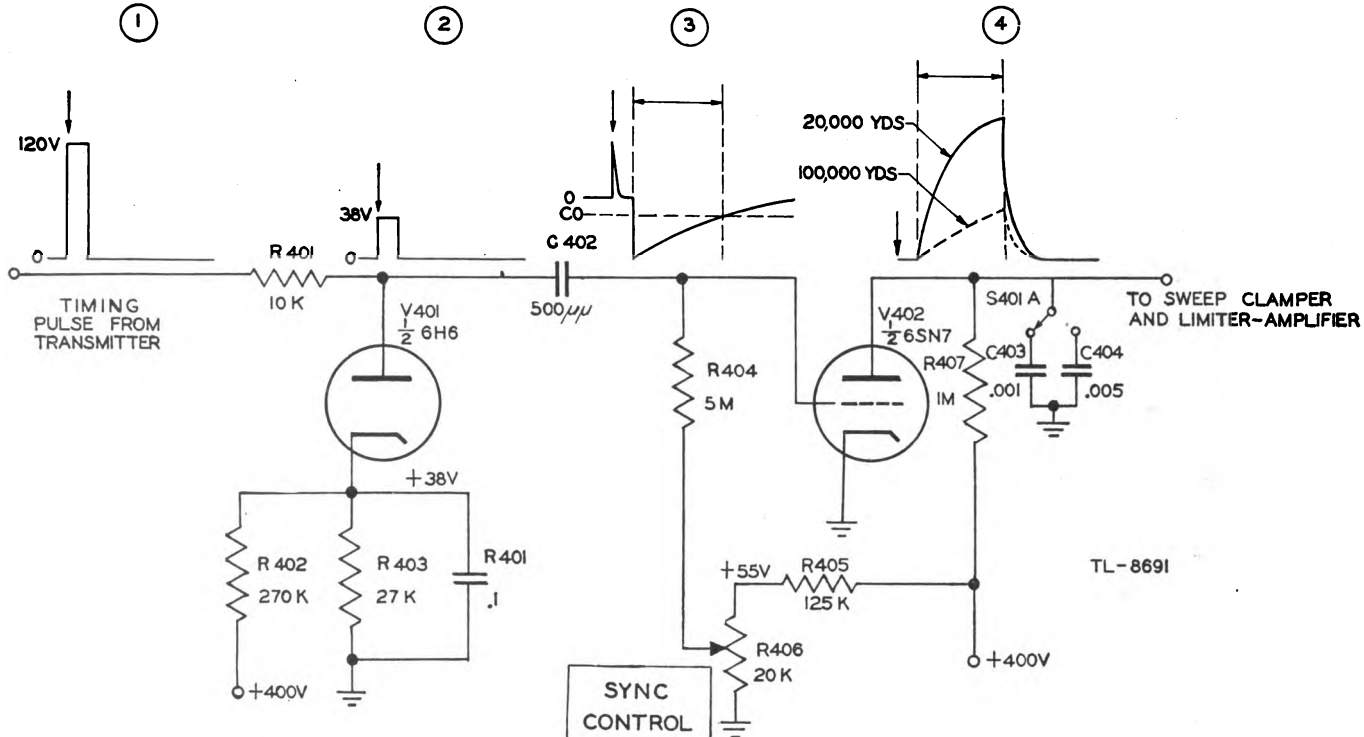

Figure 53. Sweep generator.

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5-meghom resistor R404, which limits the effective grid voltage supplied by the divider. When the positive timing pulse is applied, the grid of V402 is swung to +38 volts instantaneously and a large grid current is drawn, quickly charging the grid capacitor C402 through the low grid-cathode resistance. This action can be followed in the waveform of figure 53③. As C402 becomes charged to the full 38 volts the grid is returned to approximately zero potential. At the end of the timing pulse the grid is instantly driven to −38 volts, which cuts off the tube. The charge on the grid capacitor begins to leak off through the large grid resistor, R404, to the +400-volt supply.

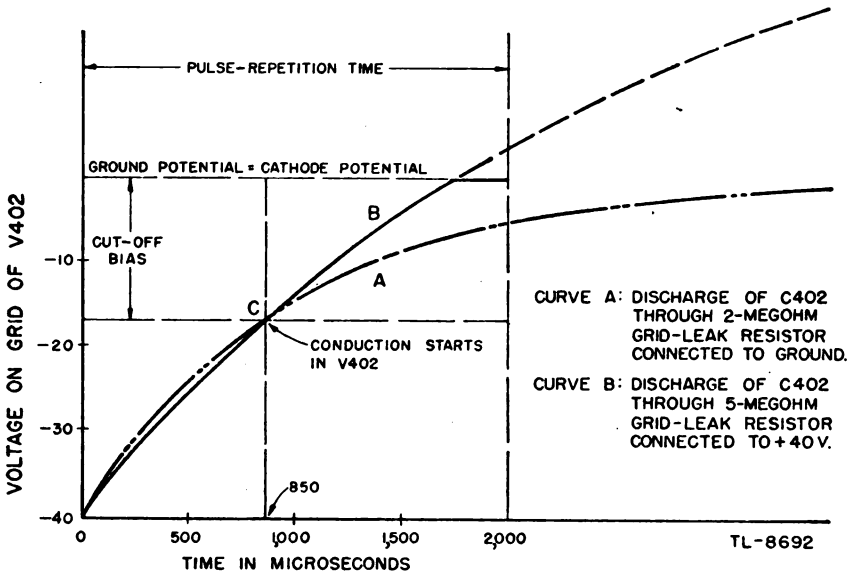

Figure 54. Effect of R404 on discharge rate of C402.

(3) When tube V402 is cut off because of the discharge of capacitor C402, the sweep-generating capacitor, C403 or C404, begins to charge through resistor R407 from the plate supply. The charging continues until tube V402 conducts and acts as a parallel low resistance to remove the charge. The *duration* of sweep voltage rise therefore depends on the length of time necessary for the negative grid voltage caused by the discharge of capacitor C402 to reach cut-off for tube V402. This time is made greater than the 610 microseconds necessary for an echo to return from a target at the maximum range of 100,000 yards. For example, in figure 54 it has been assumed that V402 begins to conduct 850 microseconds after the end of the transmitted pulse. One method of causing the negative grid voltage to reach cut-off (point *C*) in 850 microseconds is to discharge

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capacitor C402 through a 2-megohm resistor connected to ground. The discharge takes place along curve *A*. A second method is to use a larger resistor which is connected to a positive voltage source. The coupling capacitor then discharges to zero and attempts to charge in the opposite direction. Curve *B* represents the discharge of C402 through a 5-megohm resistor connected to +40 volts. When the grid voltage is reduced to zero, it is held there by grid-current action discussed in (2) above. Figure 54 indicates that curve *A* and curve *B* both reach cut-off bias in 850 microseconds. However, curve *A* shows that the grid of V402 can never reach ground potential within the pulse repetition time, while curve *B* can. It is desirable that the grid be returned to ground potential within the pulse-repetition time in order that the plate resistance of V402 may be low for a sufficient time to discharge the sweep capacitor. The voltage waveform at the grid of V402 is as shown in figure 53③.

(4) While V402 conducts, the voltage between its plate and ground is low. When the tube is cut off, the voltage from plate to ground rises as fast as C403 can be charged. The rise follows an exponential curve with a slope determined by the time constant involved. Curves of two different slopes may be obtained by selecting one of the two capacitors C403 or C404. The voltage at the plate continues to rise exponentially toward +400 volts as long as the tube V402 remains cut off. When the charge on C402 has decayed sufficiently to allow the tube to conduct again, C403 discharges through the sweep-generator tube, and the voltage at the plate of V402 drops rapidly to its normal value. The waveform at the plate of V402 is shown in figure 53④. The magnitude of the plate waveform depends on the capacitor selected.

c. Sweep clamper and limiter amplifier. (1) The waveform in figure 53④ shows that the amplitude of the 20,000-yard sweep is much greater than that of the 100,000-yard sweep at the output of the sweep generator, but that the time in which both voltages rise is the same. This waveform is repeated in figure 55①. In order to produce a sweep voltage for the 20,000-yard range, the rise in voltage shown by the solid line must stop after 122 microseconds. Similarly, to produce the 100,000-yard sweep, the rise of the voltage represented by the dotted line must stop after 610 microseconds. The limiter-amplifier accomplishes this result by limiting the applied signal at the proper time.

(2) If a resistor were used as a grid leak, capacitor C405 would charge to some extent during the positive swing of voltage caused by the applied signal. This charging would distort the linear rise of voltage. To avoid this distortion, the diode V403 is used as "one-way" grid leak. No current can flow in this type of grid leak during the

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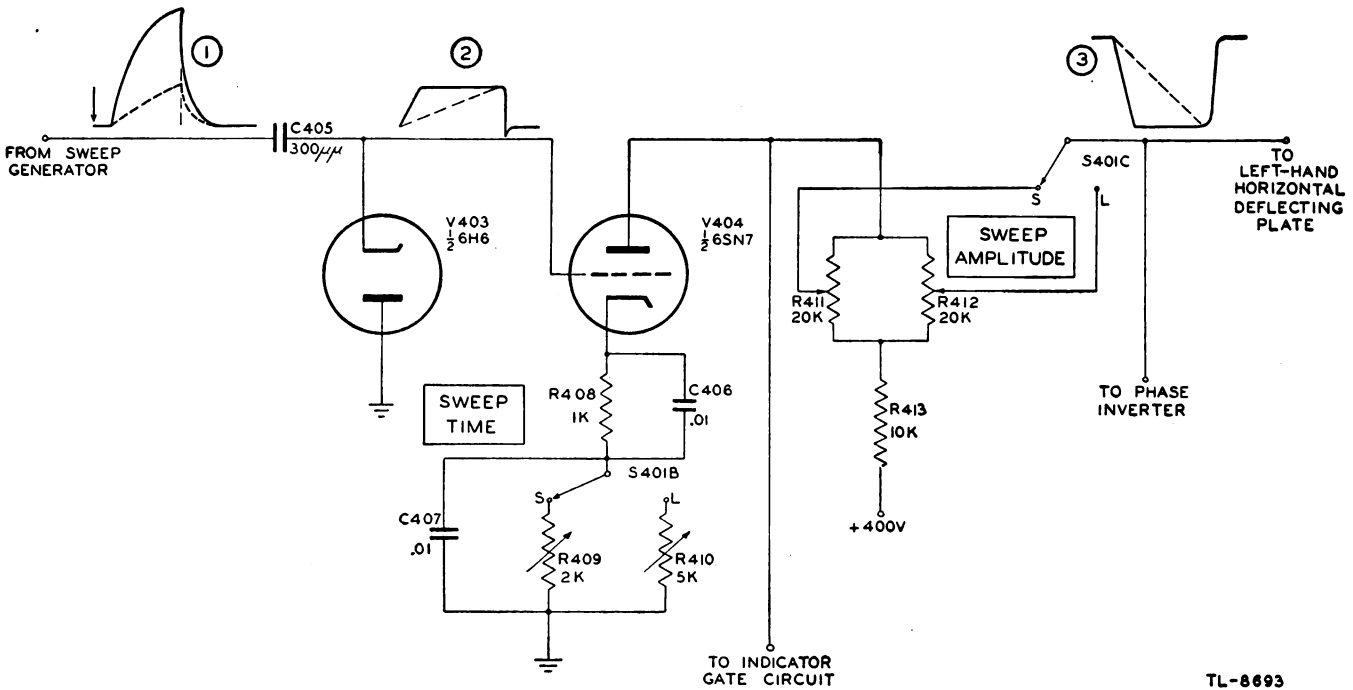

Figure 55. Sweep clamper and limiter-amplifier.

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positive swing of the grid signal since the cathode of the diode is more positive than the grounded plate. The action of V403 may be considered to be that of a clamping tube which prevents the grid of V404 from going negative with respect to ground. Any change which is put on C405 by grid current flow is removed almost instantly with the removal of the driving signal. Thus the grid of the amplifier tube must be held to ground potential in the absence of a signal on the grid.

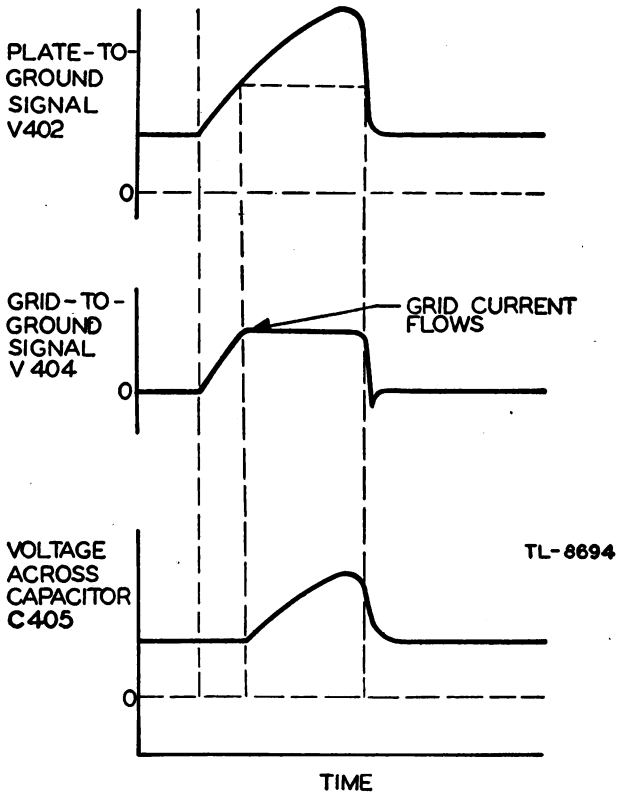

Figure 56. Grid limiting in V404.

(3) Since the sweep clamper, V403, cannot conduct during the positive swing of the signal (fig. 55①), the signal is applied to the grid of tube V404 without change until grid current begins to flow. Capacitor C405 is relatively small so that when grid current does flow the capacitor charges as fast as the voltage rises. The result is to increase the signal on the grid of limiter-amplifier tube V404 until grid current flows, and to absorb any further increase in capacitor C405 (fig. 56). The clamper tube, V403, removes this charge during the negative signal swing.

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(4) The value of applied signal which will produce grid current is controlled by varying the bias in the grid-to-cathode circuit. Figure 57 shows the effect of variation in bias on the time during which the grid signal rises. The more negative the bias used, the longer the time that the grid signal can rise. This bias is produced and controlled by means of resistors R408 and R409 or R410 in series with the cathode (fig. 55). Capacitors C406 and C407 are used to provide partial degeneration by means of which the exponential rise is made very nearly linear. The resistors R409 and R410 are called sweep-time controls since they set the speed with which the beam is traced across the oscilloscope screen.

(5) The limited voltage swing which is effective between grid and cathode is amplified and inverted by tube V404. The signal appearing on the plate normally has a different magnitude for the two ranges. The amplitudes must be the same, since the length of the sweep trace

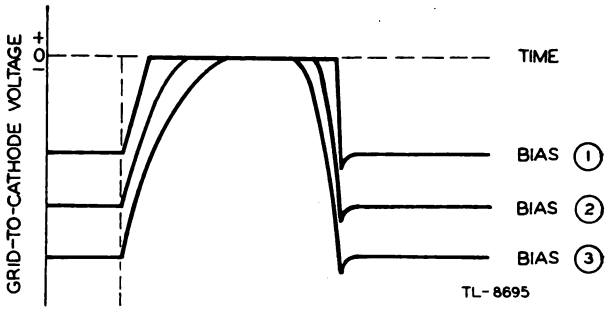

Figure 57. Bias control of limiter amplifier.

depends on the magnitude of the voltage applied between the deflecting plates. Resistor R411 is used as a plate load for producing the 20,000-yard sweep, and as a voltage divider to provide the proper sweep amplitude for the indicator. R412 performs a similar function for the 100,000-yard range. The switch S401C selects the proper output and supplies it to the left horizontal deflecting plate of the oscilloscope (fig. 55③).

d. Phase inverter. (1) The sweep is applied in push-pull to the deflecting plates to avoid the defocusing effects explained in paragraph 78a, TM 11–466, and NavShips 900,016. In order to obtain a positive-going voltage wave to apply to the right-hand horizontal deflecting plate, it is necessary to change the polarity of the output of the sweep-amplifier tube (fig. 58).

(2) The voltage divider R414 and R415 reduces the amplitude of the voltage applied to the phase inverter tube V405 by a factor equal to the gain of this tube. The voltage divider cuts down the waveform ① in figure 58 by a factor of approximately 11. The small-amplitude

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positive ② is applied to the grid of V405 for amplification. By proper design of the plate-load resistor and the cathode resistor, the gain of this stage is made approximately equal to 11. The output waveform ③ is of the same amplitude as the waveform ①, but it is of the opposite polarity.

e. Indicator gate. (1) It is usually desirable to have the trace visible on the indicator screen only while the spot is being swept from left to right. Such an arrangement eliminates both the bright spots that could appear at the ends of the sweep and the faint return trace. The waveforms in figures 53 and 58 show that the spot rests at the left end of the trace until the sweep parts, and for the 20,000-yard sweep it rests at the right end until the voltage drops. The bright spots that would appear because of these momentarily steady voltages would render the observation of the picture on the screen difficult.

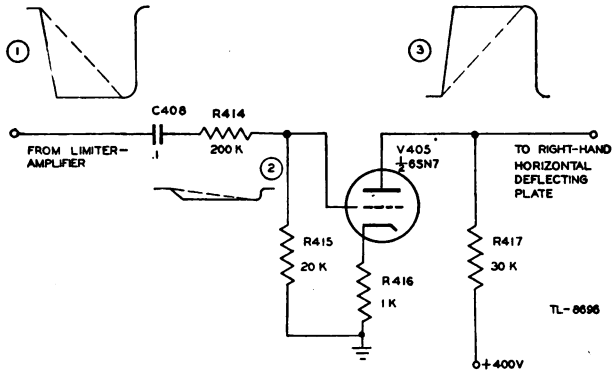

Figure 58. Phase inverter.

(2) The bias on the cathode-ray tube is normally such that no electrons strike the screen; that is, the tube is normally biased beyond cut-off and therefore no light is omitted from the screen. The output of the gating stage reduces the bias on the grid of the cathode-ray tube so that electrons can flow in the beam. The change in bias occurs at the instant at which the sweep voltage begins to move the spot across the screen. To produce this change in bias at the proper instant, the negative-going sweep from the plate of V404 is differentiated. The output of the differentiating circuit, C409 and R418 (fig. 59), is dependent on the rate of change of voltage applied to it. If the voltage changes rapidly, a large output is obtained. If the voltage does not change, no output is obtained. Therefore the sloping parts of waveform ① in figure 59 produce the pulses in waveform ②, while the horizontal parts of waveform ① produce no output. By this means, the plate current in V406 is reduced during the actual sweep time, and the voltage at the plate of the tube rises and remains high during the

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sweep time only. The positive pulse that appears at the plate of V406 (waveform ③, fig. 59) is applied to the grid of the cathode-ray tube. The time relationships of these waveforms are seen in figure 60. Thus, electrons are allowed to flow, and a trace is produced on the face of the cathode-ray tube only during the short time that the sweep voltage is changing. At the end of the sweep, a bright spot is prevented by the

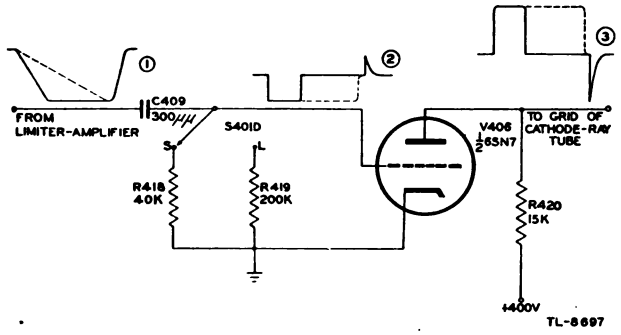

Figure 59. Differentiator and amplifier as indicator gate circuit.

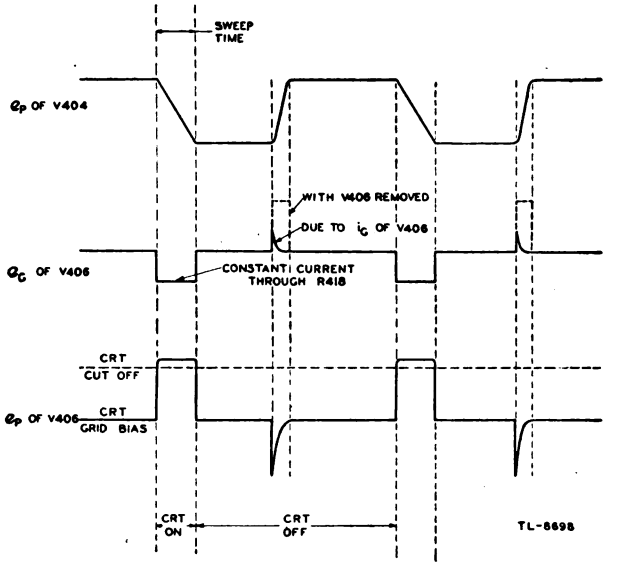

Figure 60. Voltage waveforms of indicator gate circuit.

fact that the grid voltage of the cathode-ray tube falls rapidly to a value well beyond cut-off, eliminating the electron beam.

(3) Since the voltage changes at a slower rate for the 100,000-yard sweep than it does for the shorter range, the output of the differentiating circuit would be small if the constants of the circuit were not changed. Therefore, when the long-range sweep is used, a larger resistor, R419 (fig. 59), is switched into the differentiating circuit so that

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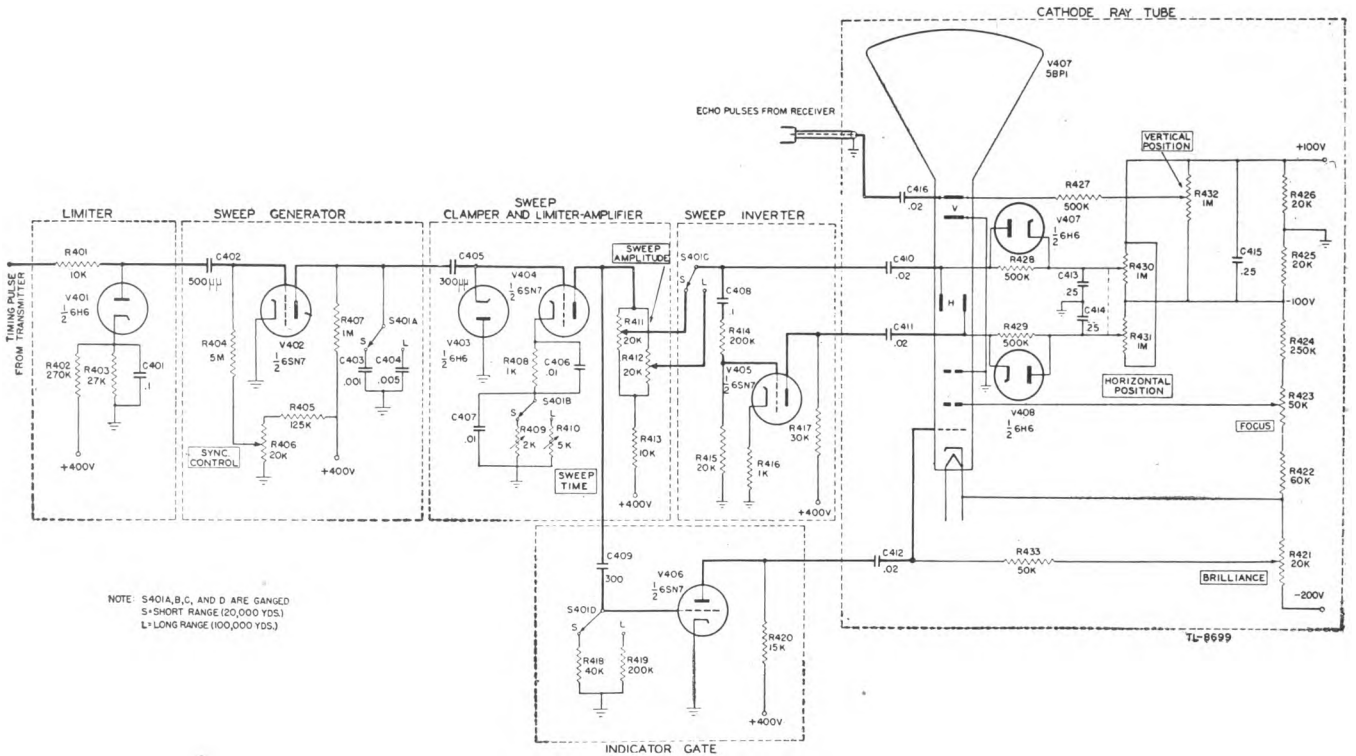

Figure 61. Complete schematic diagram of indicator.

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a pulse of practically the same amplitude is applied to the amplifier as in the former case.

f. Cathode-ray tube. The circuit associated with the cathode-ray tube, which is shown in the complete indicator circuit diagram (fig. 61), is quite conventional. Because push-pull deflection is used in the horizontal direction, the centering voltage is also push-pull. The blocking capacitors C410, C411, and C412 are used to prevent the direct voltages on the oscilloscope elements from affecting the connected circuits.

g. Operation of indicator. (1) A transparent scale, on which lines are etched at equal intervals, is placed over the face of the cathode-ray tube (fig. 62). These lines are designed to be 2,000 yards apart for the 20,000-yard sweep and 10,000 yards apart for the 100,000-yard sweep. The video output pulses from the receiver

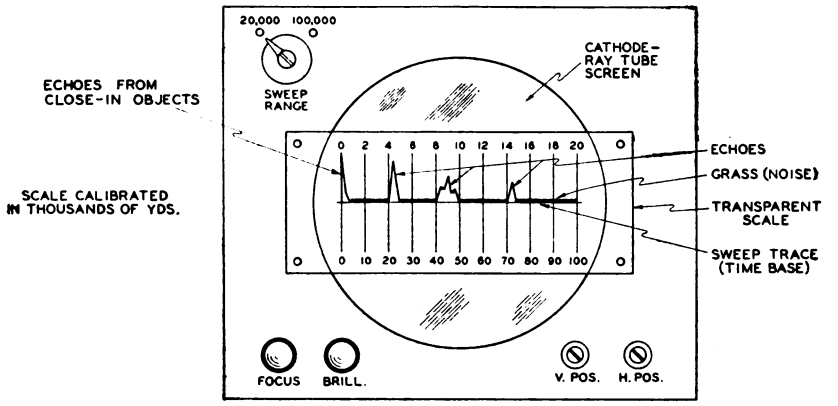

Figure 62. Appearance of indicator screen.

cause vertical deflections of the trace. The ranges of the targets from which these echo pulses come can be estimated from the position at which they appear on the trace relative to the overlaid scale.

(2) The length of the trace is adjusted on the 20,000-yard sweep by variation of both R409, SWEEPTIME, and R411, SWEEP AMPLITUDE, (fig. 61). A calibrator may be used to provide range-mark pulses, called "pips" or "blips," which are spaced at equal intervals. The speed of the sweep is then adjusted by means of R409 to make the range marks line up with the marks on the scale. During this process, the SWEEP AMPLITUDE control and the HORIZONTAL POSITION control R430–R431 must be adjusted so that the length of the sweep is always contained within the extreme marks on the scale. After the sweep has once been calibrated in this way, it should need no further adjustment except for routine checks.

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(3) The clamping diodes V407 and V408 prevent a shift in the position of the sweep trace when the range is changed. These diodes insure that the sweep voltage on each horizontal deflection plate always starts from the voltage determined by the setting of the two positioning potentiometers, resistors R430 and R431.

(4) The control knobs on the front of the indicator are the sweep range, the focus, and the brilliance. The position potentiometers need adjustment infrequently. They are therefore made adjustable only by screw driver. Only the controls which the operator needs to operate the equipment are made accessible.

(5) The SWEEP-RANGE control operates the switch S401 (fig. 61). There are four sections of this switch, which are shown as S401A, B, C, and D. All sections are operated simultaneously since they are all on the same shaft. The two positions of the switch are indicated as *S* and *L*. The letter *S* indicates the short or 20,000-yard range, and the letter *L* indicates the long or 100,000-yard range.

20. POWER SUPPLY.

a. General. A variety of direct voltages is required to operate the radar equipment. A high-voltage source, which is capable of delivering a large current for a short interval of time, is required for the transmitter. It is not important that the regulation or the amount of ripple voltage of this power supply be controlled carefully. Another source of power at a high voltage, but with an almost negligible current drain, is needed for the accelerating voltage in the cathode-ray tube. Regulation of this source is no problem because of the constant small load, and the ripple voltage is eliminated because the filter capacitor is kept charged almost to the peak voltage. However, for the plate voltage supply for the receiver and indicator, a source of good regulation and very small ripple voltage is needed. In addition to these power supplies which furnish the direct voltages, suitable transformers must be provided to supply the heater power for the various tubes. A schematic diagram of the various power-supply circuits is shown in figure 63.

b. Transmitter. Since the average current drain of the transmitter is low, and because it is not absolutely necessary to maintain a constant value of direct voltage at the plates of the transmitter tubes, a voltage-doubler power supply is adequate for the transmiter. The action of this circuit is explained in section VI, TM 11–466, and Navships 900,016. The resistors R601 and R602 are used to limit the peak current that passes through the rectifier tubes to charge the capacitors C601 and C602.

c. Cathode-ray tube. The simple half-wave rectifier V603 maintains a practically full charge on the filter capacitors because the

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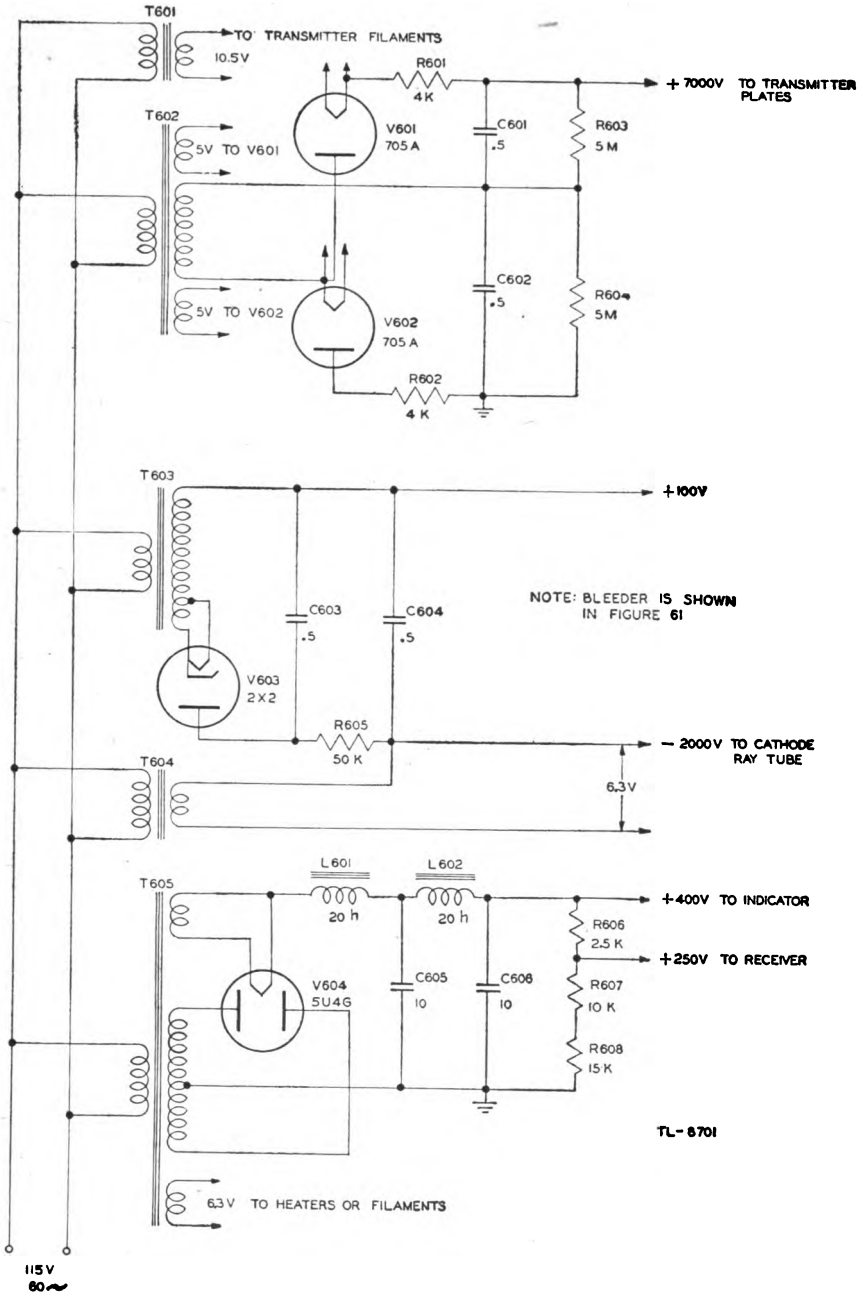

Figure 63. Schematic diagram of power-supply circuits.

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current drawn by the cathode-ray tube and by the bleeder, located in the indicator, is very small. Because the current drawn is small, it is economical to use the smoothing resistor, R605. Transformer T603, used to step-up the line voltage, is a special type in which a few turns near one end of the secondary winding are made of large wire. Across these few turns a voltage of 2.5 volts is induced, so that the filament of the type 2 x 2 tube may be heated from this source of power. The other end of the winding is held at a potential 100 volts positive with respect to ground by the voltage drop that occurs in a part of the bleeder (fig. 61).

d. Indicator and receiver. The current drain of the receiver and the indicator is fairly high. Therefore, a tube which is capable of supplying a large continuous current must be used in this power-supply circuit. A full-wave rectifier V604 is used to reduce the ripple in the output, and a choke-input filter is used to improve the regulation. Resistors R606, R607, and R608 serve as load resistance to provide a constant load on the rectifier so that the filter capacitors cannot charge to the peak output voltage of the rectifier when no external load is connected. These load resistors aid the voltage regulation of the rectifier and prevent abnormally high voltages from being impressed on the receiver and indicator tubes before they are properly heated. These resistors serve also as a voltage divider to provide the 250 volts for the receiver.

e. Possible modifications. (1) In this simple radar set all of the rectifier power supplies are shown lumped together in one chassis. In practice they are seldom lumped because it is unwise to extend high-voltage cables over a greater length than is absolutely necessary. For this reason the rectifiers are usually distributed throughout the equipment. In such an arrangement, only the 115-volt primary voltage need be distributed among the several units.

(2) Generally it is desired to maintain the plate voltage on the tubes in the receiver at a very constant value. Frequently an electronic voltage regulator is used for this purpose. If a regulated power supply is used, the rectifier connected to T605 is modified to supply only 400 volts, and a separate rectifier circuit is used with the electronic regulator.

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Section IV

Detailed study of externally synchronized microwave radar system

21. GENERAL.

a. Application. (1) The radar system described in this section is designed for installation in an aircraft to enable it to search for surface vessels. This type of radar equipment is called aircraft to surface vessel, or simply ASV. Because the set is used in aircraft, it must be light in weight and small in size. These limitations did not affect the design of the radar system discussed in section III, since that set was intended for use at a ground station where weight and size of the equipment are of secondary importance.

(2) The indicator permits measurement of range on a 20,000-yard scale and a 100,000-yard scale. The antenna normally is rotated at a constant speed and a polar map of the area being searched is drawn on the indicator screen, with the aircraft constituting the focal point or center of the map. All reflecting objects within range of the system appear on the screen of the cathode-ray tube as bright spots of light whose relative position with respect to the center of the map is an indication of the range and bearing of the reflecting objects from the aircraft. An indicator in which a radial sweep is rotated to produce a plan view of an area as called a *plan position indicator* or PPI.

b. System constants. (1) In order to limit the antenna array to a reasonable size for installation in an aircraft and to permit the detection of small targets such as submarine periscopes, a carrier frequency of 3,000 megacycles per second has been selected. A 2-microsecond pulse of radio-frequency energy is transmitted every 1,250 microseconds. The duty cycle for the transmitter is therefore 0.0016, which permits an output peak power of 50 kilowatts to be generated from an average input power of approximately 250 watts.

(2) The pulse-repetition frequency of 800 pulses per second allows ample time for echoes from all targets within the maximum range of the set to return between transmitted pulses, yet the pulses are repeated at a sufficient rate to give a clear target definition on the indicator tube. By sweeping the antenna in azimuth at a maximum rate of 20 revolutions per minute, several pulses of energy can strike each object in the area to be searched, so that everything in that area should

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be detected. If the antenna were rotated at an excessively high speed, the beam might be displaced in azimuth so far from one pulse to the next that objects near the extreme range of the equipment could remain undetected until their range was reduced.

c. System components. (1) The components which make up the system are shown in figure 64. Note that the functions which must be accomplished in this system are identical with those of the system discussed in section III. The difference between the two systems is in the manner of performing the necessary functions. In this system examples of the techniques usually employed in a microwave system are illustrated in contrast to the long-wave techniques discussed in section III. In order to make this section as useful as possible in showing typical radar circuits, an external timer and a different type of indicator are shown.

(2) The system requires an 800-cycle-per-second motor-driven generator capable of delivering approximately 10 amperes at 115 volts.

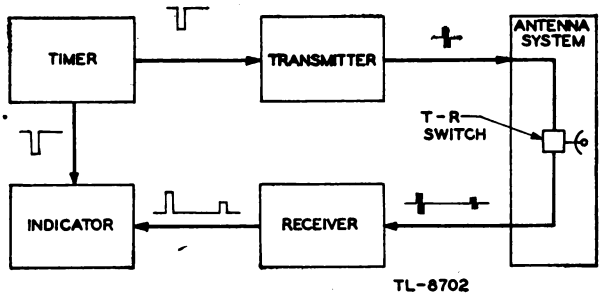

Figure 64. Block diagram of externally synchronized radar set.

A 24-volt, 8-ampere, d-c source of power is required for operating the antenna motors. Transformers and rectifiers are included in the various components to supply the necessary voltages to the vacuum tubes.

(3) The timer produces 800 sharp negative pulses per second to trigger the transmitter and the indicator. The 2-microsecond r-f pulse is generated in a magnetron and is radiated from a paraboloidal reflector. Since the same antenna is used for transmitting and receiving, a T-R switch is necessary to protect the receiver during the transmitted pulse. The output of the receiver is applied to the grid of an electromagnetic cathode-ray using type PPI-scan to cause a spot of light to appear on the screen when an echo is received.

22. TIMER.

a. General. (1) The timer performs the functions of establishing the pulse-repetition rate of the radar system and of synchronizing the actions of the other components to the transmitter. The

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most obvious synchronizing action is that of causing the sweep in the indicator to start at exactly the same instant that the transmitter produces a pulse of r-f energy. However, the production of the sweep and of the gate voltage associated with the sweep will be treated during the discussion of the indicator. The amplification of the trigger pulse formed by the timer will be treated during the discussion of transmitter, with which this action is closely associated.

(2) The block diagram of figure 65 shows the circuits used in the timer to produce the trigger pulse. The master oscillator in this system generates an 800-cycle sine-wave voltage. The sine wave is ap-

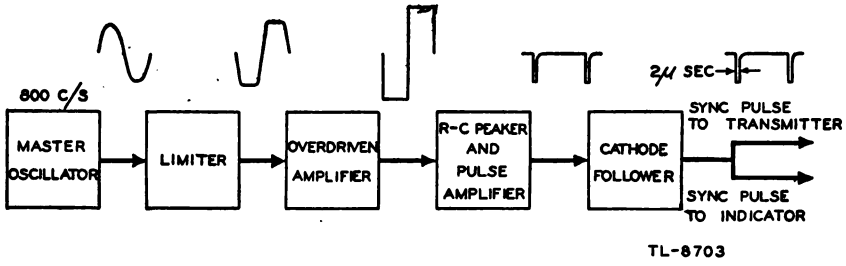

Figure 65. Block diagram of timer.

plied to a limiter stage to produce a waveshape which is approximately square. An overdriven amplifier is used to make the sides of the square wave more nearly vertical. In this way, a sharp pulse of approximately 2 microseconds duration with a definite leading edge may be derived from the R-C peaker which follows the overdriven amplifier. The positive pulse of the peaker output is selected and amplified. This pulse is used to trigger the transmitter and to synchronize the start of the indicator sweep. The complete schematic circuit diagram of the timer is shown in figure 66.

b. Master oscillator. (1) The circuit used to control the repetition rate is a phase-shift oscillator (fig. 67). The output of the oscillator is a sine wave of good frequency stability, which produces a sweep trace free from jitter.

(2) Oscillations are produced by coupling the plate of tube V101 back to the grid through an R-C bridge network. The network reduces the signal from plate to ground by an amount equal to the gain of the tube, and produces a 180° phase shift only at 800 cycles per second. A negative feedback voltage, which is essentially constant for all frequencies, is developed across the unbypassed cathode resistor R105. This feedback maintains a sinusoidal output at the plate of the tube V101. The combination of a phase shift other than 180° with the negative feedback voltage reduces the tendency of the system to oscillate at any frequency except 800 cycles per second. The constants of the feedback network determine the frequency at which

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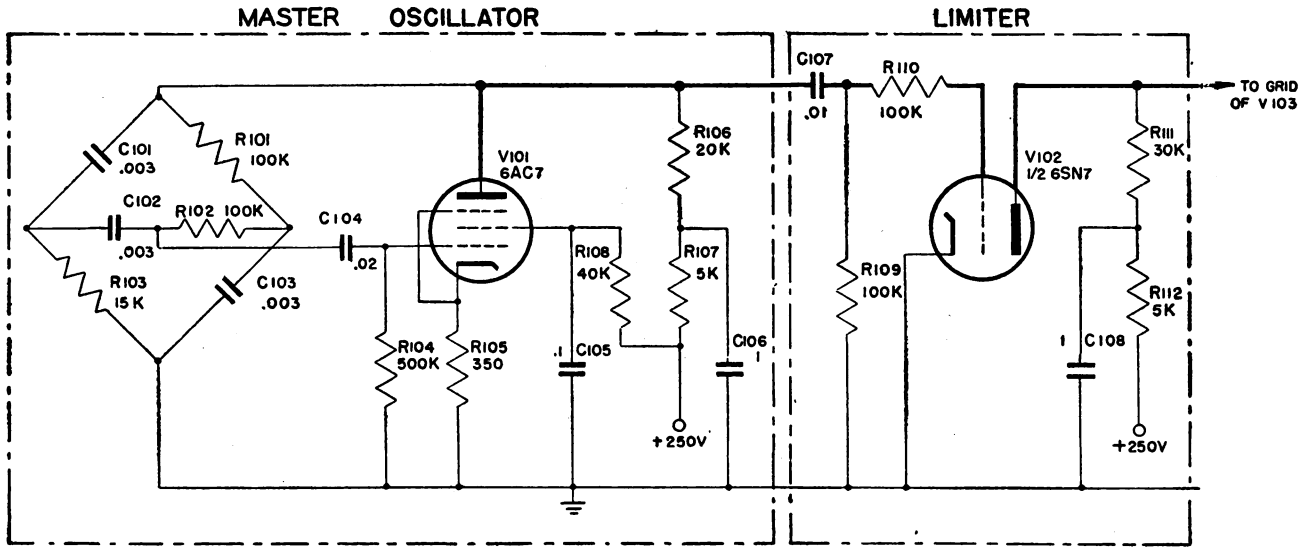

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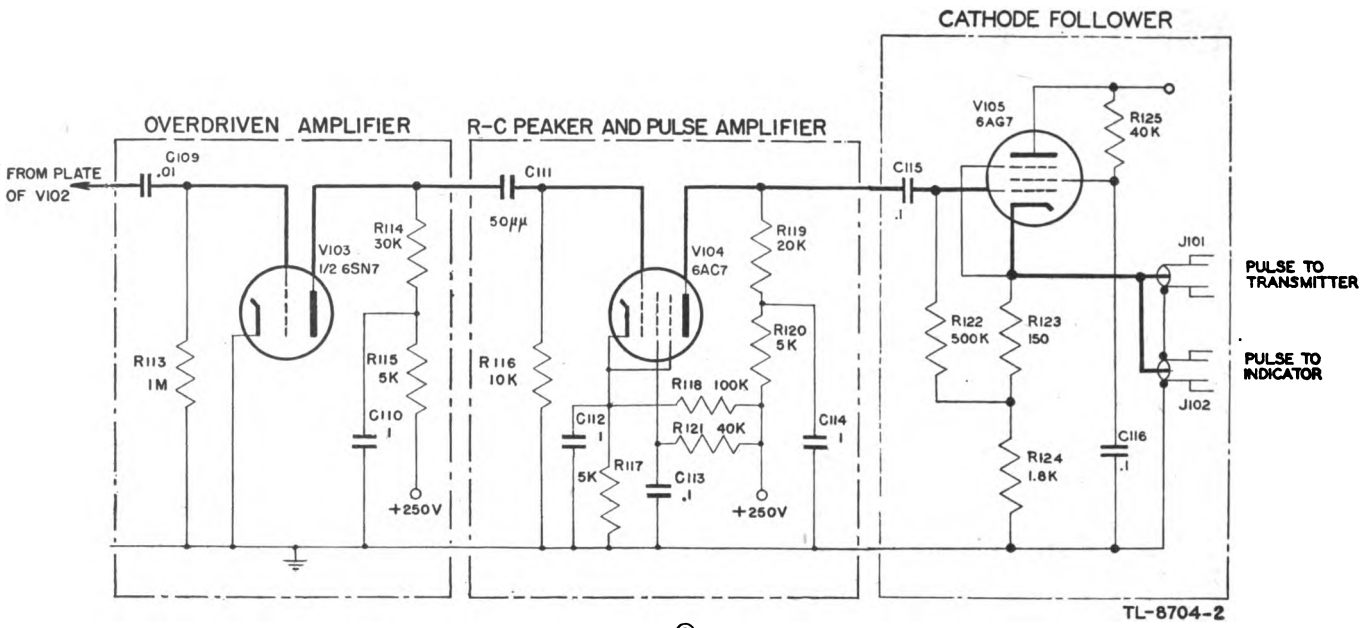

Figure 66. Schematic circuit diagram of timer.

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oscillations take place, while the resistance of R105 determines the amplitude of these oscillations. The output voltage is developed across the plate load resistor R106.

(3) The combination of R107 and C106 in the plate circuit of the tube acts as a filter to prevent feedback through the power supply. This filter is desirable to prevent interference with other circuits operated from the same power source. The low reactance of C106 at the frequency of the oscillator effectively short-circuits the alternating voltage which tends to appear at the junction of R106 and R107. Capacitor C106 can be considered as a battery, because the voltage between its terminals cannot change until charge has been added or removed. Since the resistance present in the circuit prohibits any

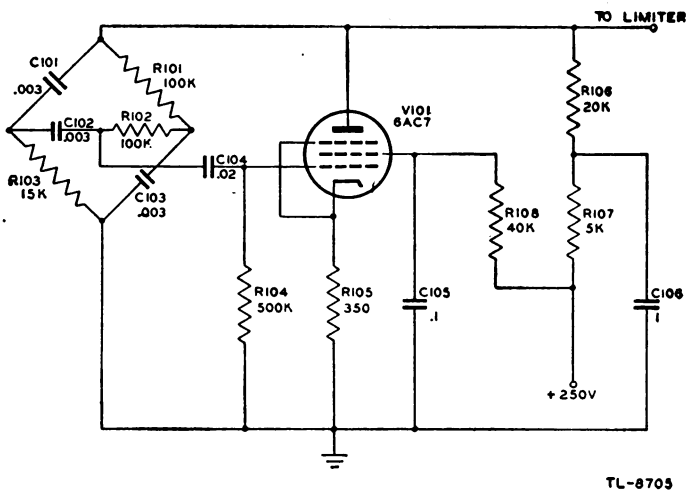

Figure 67. Schematic circuit diagram of master oscillator.

instantaneous change, the voltage across the capacitor is held practically constant.

c. Limiter. (1) The first step in producing trigger pulses from the sine-wave voltage is to convert the sine wave into a square wave. To make this conversion, the amplitude of both the positive and the negative alternations of the sine wave must be limited. The limiter used in this timer is shown in figure 68.

(2) The limiter tube is operated with zero fixed bias, and develops grid-leak bias due to grid current. The coupling capacitor C107 is charged during the positive swing of the applied signal by the current which flows through resistor R109 and through the internal grid resistance of tube V102 in series with resistor R110. During the negative swing the charge which has accumulated on C107 leaks off through resistor R109. Since the resistance for discharge is greater than the resistance for charge, a residual charge is accumulated on capacitor

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C107, which is effectively a negative bias between the grid and cathode of tube V102.

(3) The grid-leak bias which is produced by grid current flow reduces the effect of the applied sine-wave voltage in driving the grid positive. This bias represents the average about which the sinusoidal variation takes place. Figure 69① shows the average grid-leak bias as a negative voltage relative to ground, with the sine wave superimposed on it. When the grid is driven positive series resistor R110 still further limits the effective signal, because of the voltage drop across the resistor caused by grid current. This limiting is illustrated in figure 69① by the reduction of the positive peak from the dotted line to the solid line.

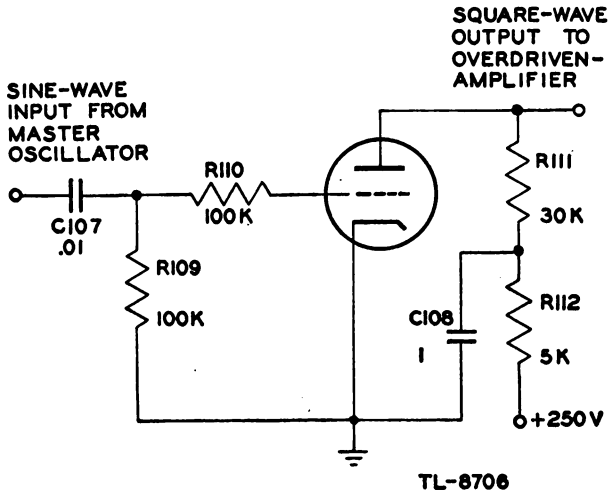

Figure 68. Schematic circuit diagram of limiter.

(4) The tube V102 reproduces the limited grid signal as the approximate square wave shown in figure 69②. The positive half cycle of the applied sine wave increases the plate current and reduces the plate voltage to a low value. The least positive portion of the plate waveform corresponds to the period of grid-current flow, and is flattened by the grid limiting. As the grid signal swings negative, plate current is reduced and finally ceases to flow when the combination of signal and bias reach the cut-off value. The plate voltage rises toward the supply voltage during this time. Since the input circuit of tube V103 is connected to the plate load resistor through coupling capacitor C109, charging current flows in R111, which prevents the plate voltage from rising instantaneously.

d. Overdriven amplifier. (1) Although the sine-wave voltage is approximately squared by the limiter, the sides of the square wave are not as vertical as is desired for the production of a sharp

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trigger pulse. Therefore, the square wave produced by the limiter tube is applied to an overdriven amplifier (fig. 70) for the purpose of steepening the sides.

(2) The output from the limiter stage is a voltage of large amplitude. The plate current of amplifier tube V103 is cut off early in the negative alternation and is driven to a maximum early in the positive alternation. In addition, the grid current which is drawn during the positive half cycle of the applied voltage charges C109 through the relatively low cathode-to-grid resistance of V103. As a result, the

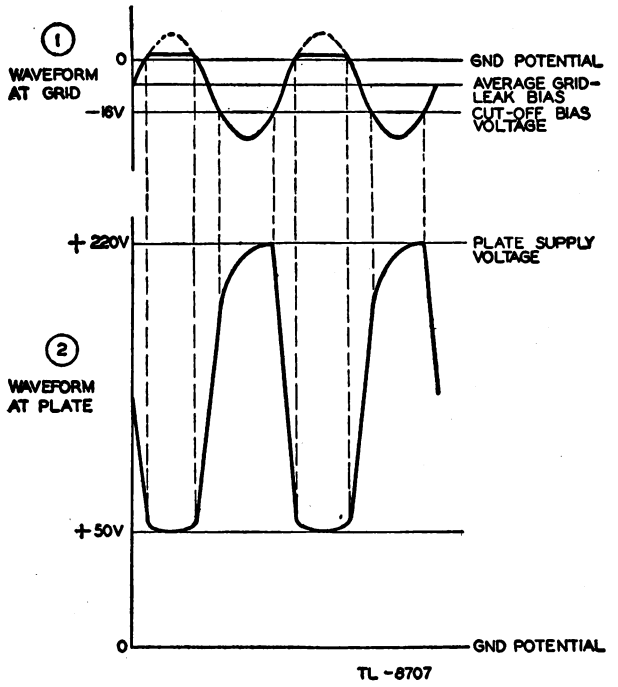

Figure 69. Waveforms in limiter tube V102.

coupling capacitor is charged to an average voltage which acts as a high negative bias for the grid of tube V103.

(3) The only bias present in the grid circuit of tube V103 is due to grid current. The plate waveform of tube V102 is distorted in passing through capacitor C109 by the charging and discharging of the capacitor (fig. 71①).

As the grid signal starts to swing positively, it is ineffective until, at time t_1, it drives the grid above cut-off. At time t_2, when the grid signal drives the grid to zero bias, grid current flows, limiting the signal until t_3. The grid is then swung negative, reaching cut-off again at t_4.

(4) Plate current begins to flow at t_1, rises to a maximum at t_2, remains practically constant until t_3, then decreases to zero at t_4. The

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drop in voltage produced by the current across resistor R114 causes the plate voltage waveform shown in figure 71②. Because tube conduction takes place entirely in the positive half cycle of grid signal, the negative portion of the plate signal is narrower than the positive portion. The plate signal of V103 is applied to an R-C peaker circuit.

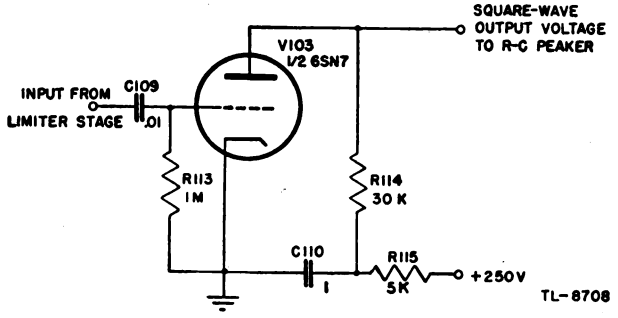

Figure 70. Schematic circuit diagram of overdriven amplifier.

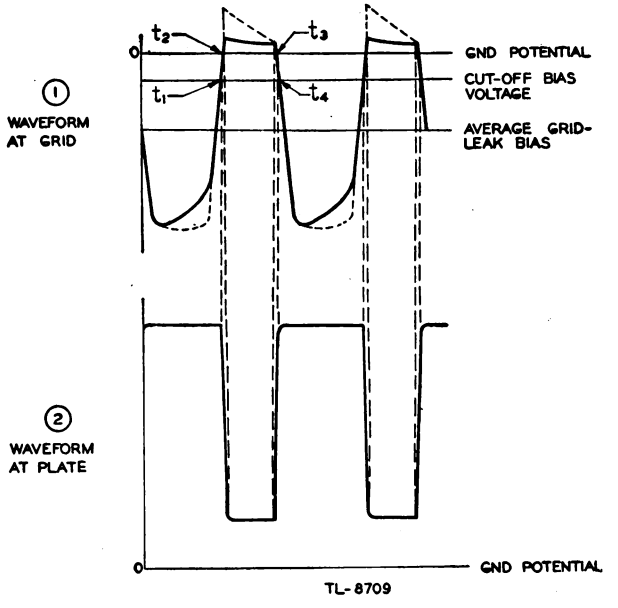

Figure 71. Waveforms in overdriven amplifier tube V103.

The important feature of the peaker is its ability to charge and discharge completely in the available time betwen signal alterations. The plate signal can therefore rise to the supply voltage only *after* the peaker circuit is charged. The leading edges of both positive and negative portions of the waveform are slightly rounded because of the short time used for charge and discharge.

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e. R-C peaker and pulse amplifier. (1) In order to produce a sharp pulse from the square-wave output of the overdriven amplifier, the time constant of the coupling circuit to the following stage is made very short (fig. 72). Because this time constant is so short, capacitor C111 charges and discharges completely and the average bias produced is negligible. The grid of the tube may therefore be considered to be at ground potential. The time constant of the coupling circuit is approximately 2 microseconds for a negative voltage swing at the grid of V104, and less than 2 microseconds for a positive swing at the grid because the low cathode-to-grid resistance shunts R116 when grid current is drawn.

(2) When the voltage applied to the coupling capacitor rises sharply (fig. 73①), a charge is quickly developed on C111. The voltage at the grid of the tube follows the charging current, rising almost instantly to its maximum value and dropping back to zero quickly (fig. 73②). In the same way, when the applied signal swings negative,

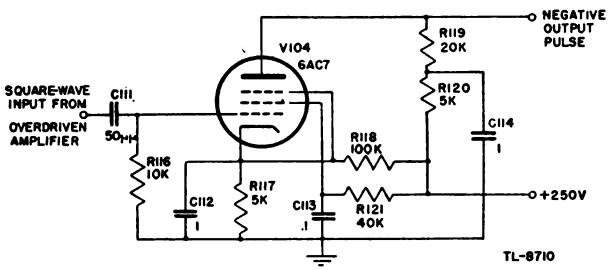

Figure 72. Schematic circuit diagram of R-C peaker and pulse amplifier.

the grid is driven below ground potential, but it returns to ground quickly because C111 discharges rapidly. The signal on the grid thus is a series of sharp positive and negative pulses.

(3) In order to eliminate the negative pulses at the input to the pulse amplifier, the tube is biased beyond cut-off. Cut-off for a 6AC7 tube with a 250-volt plate supply is approximately 6 volts. A bias of nearly 12 volts is supplied by raising the cathode potential of V104 by means of the voltage divider R117 and R118. Using this bias, the tube does not conduct until the grid is raised to a potential of +6 volts relative to ground. Hence figure 73② indicates that both the negative pulses and the broad lower portions of the positive pulses are lost because of the bias on the tube. The portion of the grid signal which tends to drive the grid more positive than the cathode is lost because of the limiting action of grid current. The peaks of the positive pulses tend to drive the grid of V104 very positive relative to the cathode, and therefore cause a large current to flow in the tube for the duration of the pulse. This large flow of current pro-

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duces a large drop of voltage at the plate of the tube (fig. 73③), so that the output is a high amplitude negative-going pulse whose duration is approximately 2 microseconds.

f. Cathode follower. (1) In this system, as in most other radar systems, the trigger pulse is conducted to the transmitter and indicator by means of coaxial cables. Cables in use have characteristic impedances in the range of 50 to 150 ohms. In order to pre-

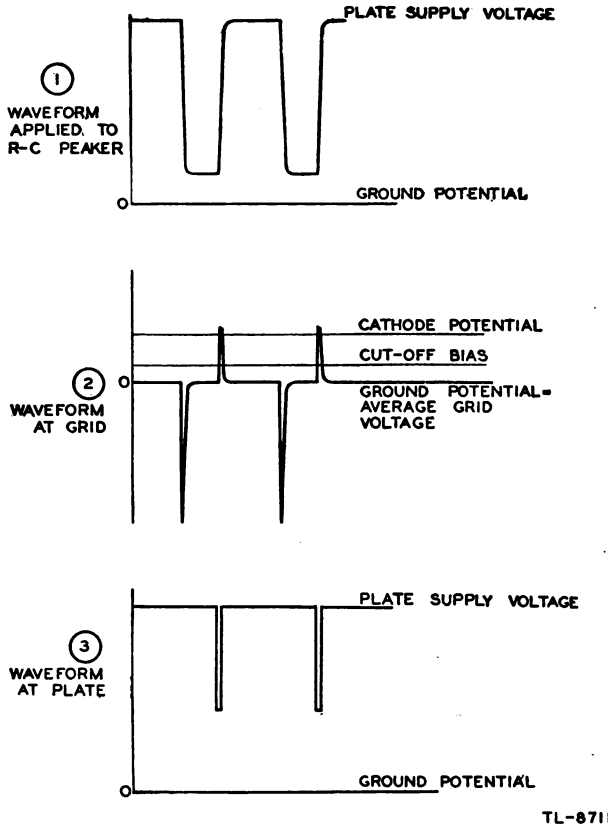

Figure 73. Waveforms in R–C peaker and pulse amplifier tube V104.

vent reflections in the cable, the terminating impedance should be as nearly equal to the characteristic impedance as is practical. A cathode follower is used as a low impedance source to furnish the output pulse of the timer to the coaxial line.

(2) Since the trigger pulse is negative-going, it is desirable to have the cathode follower normally conduct a heavy current, so that a pulse of large amplitude can be developed across the cathode resistors. The bias on V105 (fig. 74) is the voltage developed across R123 by the plate current of the tube flowing through this resistor.

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The characteristic curves of a type 6AG7 tube show that a current of 24 milliamperes flows if the bias on the tube is −3.6 volts. Therefore, the normal steady current in V105 is 24 milliamperes, since 150 ohms × 0.024 ampere = 3.6 volts. The voltage developed across R124 does not affect the bias on the tube, since it raises both the cathode and the grid above ground potential.

(3) Until the negative pulse is applied to the grid of V105, the cathode is 1,950 ohms × 0.024 ampere = 47 volts positive with respect to ground. Since the output of the pulse amplifier is more than sufficient to cut off the cathode follower, a negative-going pulse of 47 volts is produced across R123 and R124 when V105 is cut off by the applied signal. The negative pulse output of the cathode follower is coupled to the transmitter and to the indicator by coaxial lines which connect to J101 and J102.

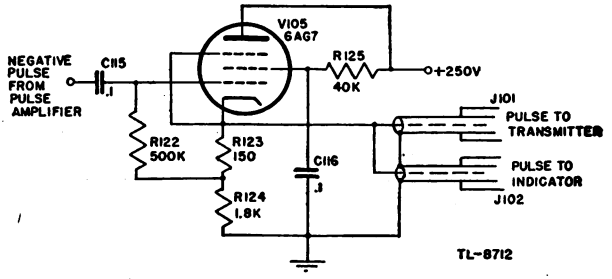

Figure 74. Schematic circuit diagram of cathode follower.

g. Power supply. The plate voltage for all tubes in the timer is supplied by the 250-volt power supply in the indicator. The heater voltage for all tubes in the timer is supplied by transformer T502 in the indicator.

23. TRANSMITTER.

a. General. (1) The transmitter generates a 2-microsecond pulse of r-f energy at a frequency of 3,000 megacycles per second under control of the timer. The peak power generated in each pulse is approximately 50 kilowatts.

(2) The r-f generator is a magnetron to which a plate voltage pulse of 12,000 volts is applied by the modulator. The modulator acts as an electronic switch. This switch is closed by a positive pulse from the driver, which amplifies the trigger pulse furnished by the timer.

b. Magnetron. (1) The operation of the magnetron used here is similar to that of the magnetrons discussed in section XII, TM 11–466 and Navships 900,016. In this tube the anode, or plate, forms an outer metal case, within which are mounted the cathode and heater. Electrically, the magnetron may be considered to be a diode and is often shown as such in schematic diagrams. Two methods of sup-

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plying plate voltage can be used (fig. 75). The first is to insulate the case from ground, connect the cathode to ground and apply the high positive potential to the case. The second and preferred method is to ground the case, insulate the cathode, and apply a negative voltage to the cathode.

(2) The magnetic field, which is applied parallel to the cathode, is produced by a permanent horseshoe magnet. The magnetron is placed between the pole faces of the magnet and fitted to them as

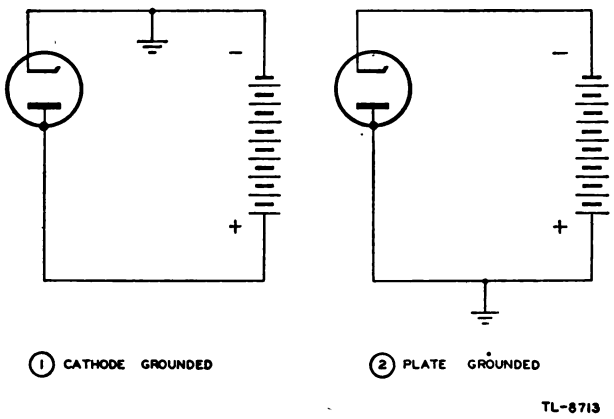

Figure 75. Methods of supplying plate voltage in magnetron circuit.

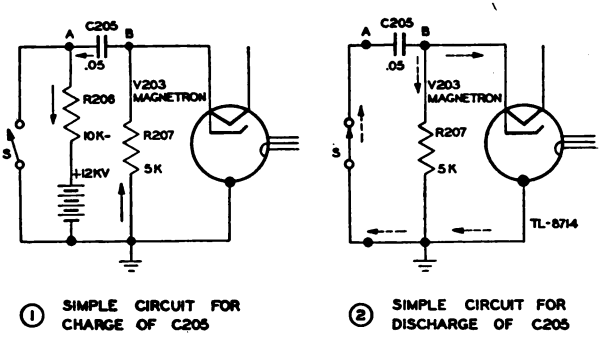

Figure 76. Equivalent circuit diagram of simple modulator.

closely as possible. The r-f energy is taken from the magnetron by coupling the transmission line to the field inside with a small loop.

c. Modulator. (1) The modulator performs the function of a switch which discharges a storage capacitor through the magnetron. In figure 76, the magnetron is shown schematically as a diode V203 and the modulator tube as a simple switch *S*.

(2) While switch *S* is open (fig. 76①), electrons flow around the circuit in the direction of the solid arrows, placing a charge on capacitor C205. During the flow of electrons, a voltage is developed

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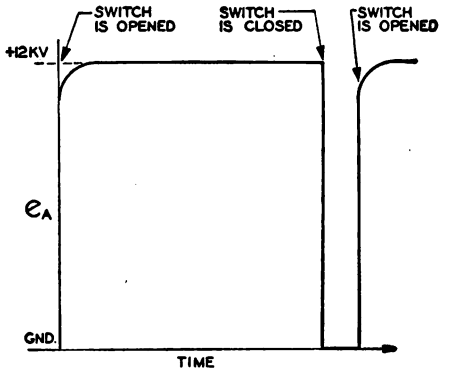
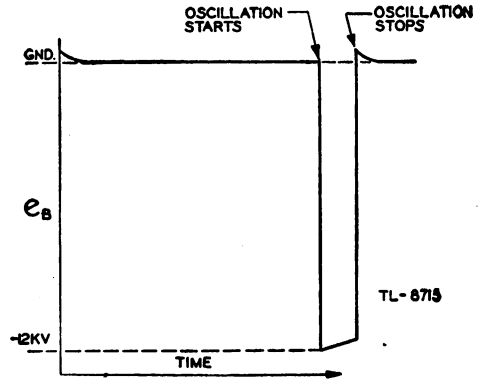
across R206 which keeps the potential of point A less than the battery voltage of 12,000 volts (fig. 77①). At the same time the drop across resistor R207 places point D at a positive potential relative to ground (fig. 77②). If the switch remains open for a long time, capacitor C205 becomes completely charged and the electron flow stops. C205 then has a potential across it of 12,000 volts, with



① VOLTAGE BETWEEN PLATE A OF C205 AND GROUND



② VOLTAGE BETWEEN PLATE B OF C205 AND GROUND

Figure 77. Waveforms in simple modulator.

point A being positive with respect to point B. In the absence of electron flow, the drop across the resistors is zero, and therefore point A is 12,000 volts above ground while point B is at ground potential. The magnetron does not conduct while the switch is open, because its cathode, point B, is either positive or at zero potential with respect to the plate, which is grounded.

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(3) If the switch is now closed (fig. 76②), point *A* of the capacitor is instantly grounded (fig. 77①). Point *B* maintains its 12,000-volt potential difference with respect to *A* by going to −12,000 volts relative to ground (fig. 77②). The magnetron can now conduct, and the capacitor is discharged through resistor R207 and the magnetron, as shown by the broken arrows (fig. 76②). By the time the switch is again opened, some charge has been removed from the capacitor and the voltage across it is less. The +12,000-volt battery starts to charge C205, instantly raising point *B* to a positive potential with respect to ground, and cutting off the magnetron. Point *A* also returns to a potential above ground.

(4) The pulse duration of the system requires that the magnetron be turned on for 2 microseconds once every 1,250 microseconds. A mechanical switch cannot readily be made which is able to operate so

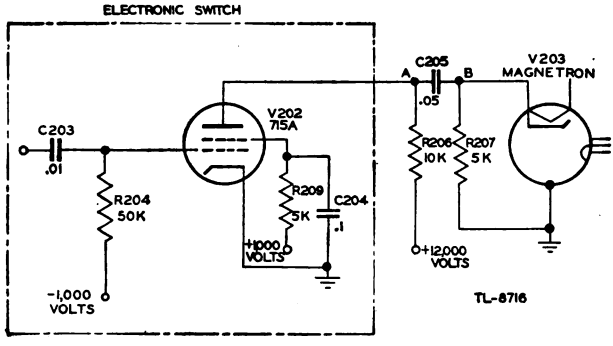

Figure 78. Schematic circuit diagram of modulator.

rapidly and at the same time handle the high power. For this reason an electronic switch is used in place of the switch *S*.

(5) The modulator and transmitter used in this system are shown in figure 78. The part of the circuit inclosed in the dotted lines is the electronic switch which replaces the mechanical switch of figure 76. The type 715A tube, V202, is normally nonconducting because of the −1,000-volt bias on its grid. In this condition it is an open switch. During the relatively long time that V202 is nonconducting, capacitor C205 charges to 12,000 volts.

(6) The modulator tube is made strongly conducting by a large positive pulse applied to its grid. During the 2 microseconds when V202 conducts, plate A of C205 is effectively connected to ground so that capacitor C205 discharges through V202 in series with the parallel combination of the magnetron and resistor R207. While the discharge is taking place, plate voltage is applied to the magnetron which, therefore, generates an r-f pulse of 2 microseconds duration.

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(7) The size of capacitor C205 is so chosen that the voltage across it will drop only 5 percent or less during the oscillation of the magnetron. This limit in the magnitude of the drop is important because if the voltage applied to the magnetron changes greatly, the frequency and the power output will change during the pulse. Such a change in frequency and power output would cause decreased efficiency in the transmitter, and consequently the radar equipment would be less effective.

(8) The power supply which furnishes the 12,000 volts to the modulator is a voltage doubler. The voltage regulation of this type is extremely poor, as the output voltage decreases rapidly with increase in output current. In order to prevent an excessive voltage drop in the voltage doubler output, resistor R206 is wire-wound. The inductive effect of this resistor aids in limiting the current drawn from the

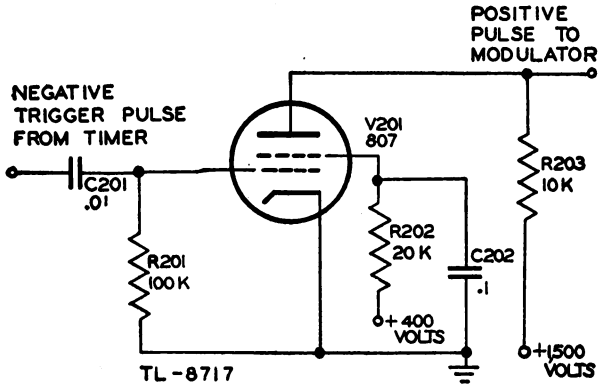

Figure 79. Schematic circuit diagram of driver.

12,000-volt power supply when it is shorted to ground through V202 during the pulse.

d. Driver. (1) The bias on the modulator tube is −1,000 volts, in order to keep this tube cut off between pulses. The 40-volt trigger pulse supplied by the timer therefore must be amplified considerably to operate the modulator tube. A pulse amplifier, called a driver, is used to increase the amplitude of the trigger pulse (fig. 79).

(2) The driver tube V201 is a type 807, which is used to provide the required amplification. The control grid is at zero bias, so that the tube normally draws a plate current of about 150 milliamperes. Because of the voltage drop produced across plate load resistor R203 by the flow of this current, the voltage at the plate of V201 is 50 volts in the absence of a signal on the grid. The resistor R202 is used to limit the screen grid current to a safe value, and the bypass capacitor C202 is used to hold the screen grid voltage at a constant value.

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(3) Under the conditions at which V201 is operated, cut-off bias is approximately −38 volts. The negative pulse from the timer is 40 volts or more in amplitude. The driver tube is cut off by the application of the negative trigger pulse. The voltage at the plate of V201 then rises to the 1,500-volt supply voltage. Thus, the output of the driver is a positive-going, 2-microsecond pulse of 1,450 volts. This large pulse is capacitively coupled to the modulator grid. The pulse is, in effect, the control which closes and opens the electronic switch.

e. Power supply. (1) The schematic circuit diagram of the complete transmitter, including necessary power supplies, is shown in figure 80. The primaries of all transformers in the power supplies are energized from the 115-volt, 800-cycle-per-second line. This line is fed by a motor-driven generator in the plane.

(2) The +12,000 high voltage for the plate of the modulator is supplied by a voltage-doubler circuit which uses two type 705A rectifier tubes. Transformer T201 is used to step up the line voltage to supply the necessary high voltage. The filaments on the two tubes are heated by the two separate secondary windings on T203. Since one filament is 6,000 volts more positive than the other, and since both filaments are at a high potential with respect to ground, the transformer must be well insulated. The resistors R209 and R210 are protective resistors which limit the peak current that can flow in the tubes to restore the charge on the capacitors C206 and C207. Since the average current drawn from the power supply is relatively small, the output voltage remains very close to twice the peak voltage of the secondary of T201. The bleeder resistors R207 and R208 afford protection to maintenance personnel since the resistors provide a path to discharge the high-voltage capacitors when the power is turned off.

(3) The plate voltage for the driver, the screen voltages for the driver and modulator, and the bias for the modulator are furnished by a full-wave rectifier. Two type 866 mercury-vapor rectifier tubes are used in this power supply because of the high current drain of the connected load. The high voltage is supplied to the rectifiers by the secondary of T202. The filament voltage for V206 and V207 is taken from another secondary winding on the same transformer. The rectifier output is filtered by L201, C208, and L202, which form a choke input filter. Capacitors C209 and C210 are used principally to stabilize the output voltages which are tapped off the voltage divider. No further filtering is necessary at the voltage divider because the screen grids which are supplied with +1,000 volts and +400 volts are each bypassed at the tube. Resistors R211, R212, R213, and R214 are so proportioned that the desired voltages can be tapped off at their junctions.

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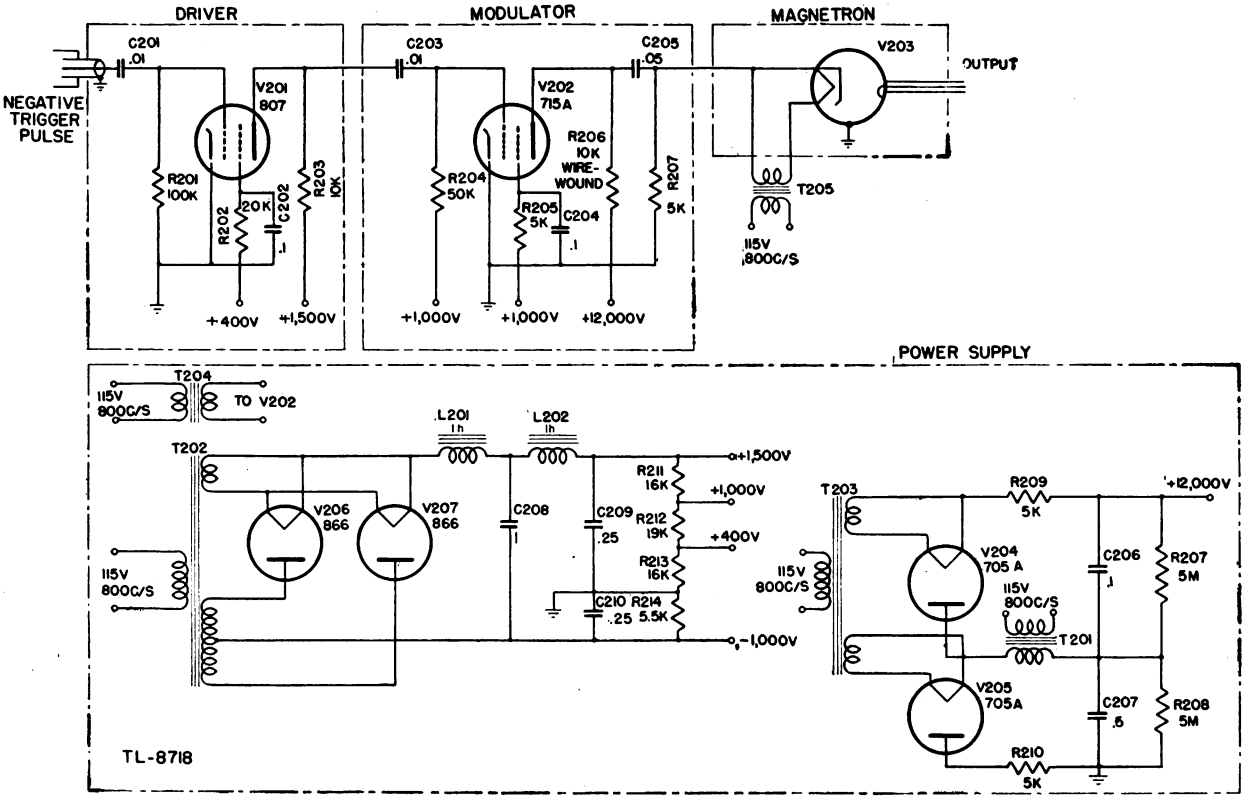

Figure 80. Schematic circuit diagram of transmitter for externally synchronized radar system.

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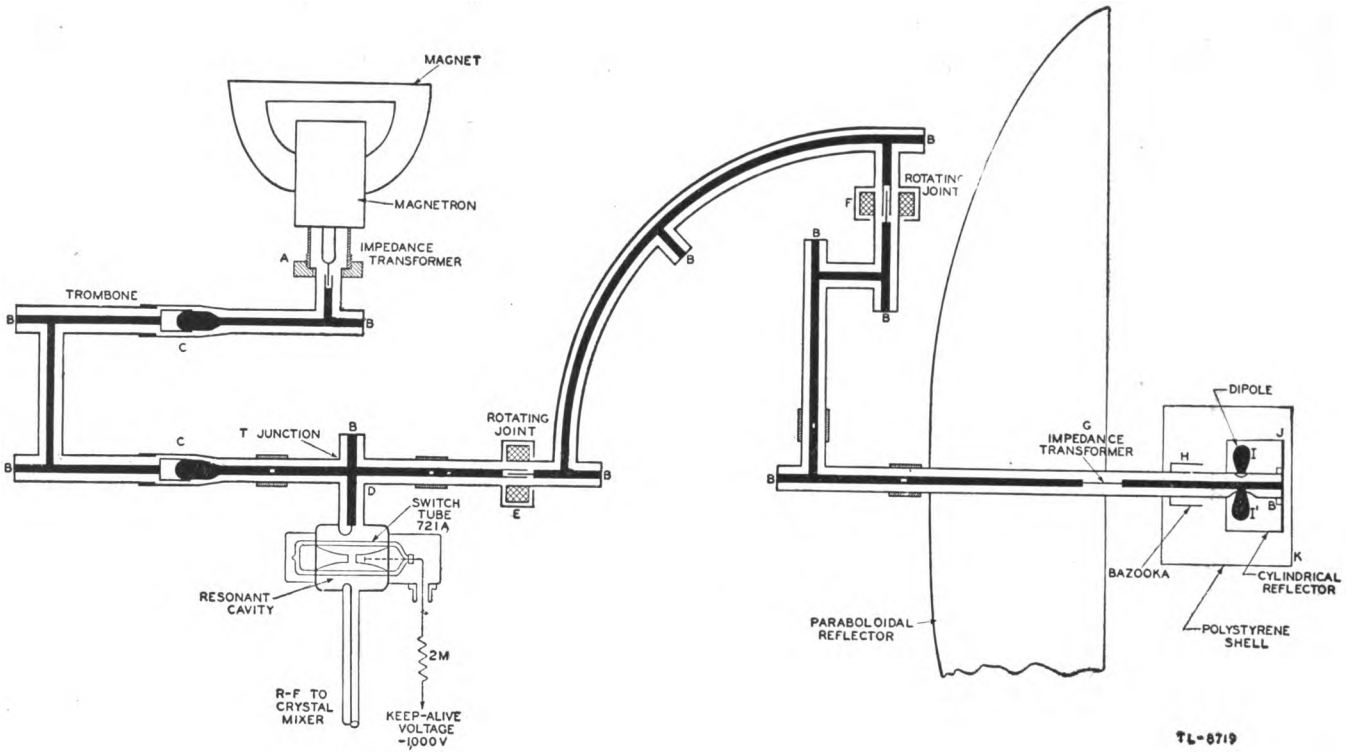

Figure 81. Schematic circuit diagram of antenna system.

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(4) The heater voltage for V201 is supplied from the 6.3-volt secondary winding in the indicator power supply. The heater voltage for V202 is supplied from the 27.5-volt secondary of transformer T204. Since the magnetron cathode is at a highly negative potential during the pulse, the heater transformer, T205, must be specially built to withstand this high voltage.

24. ANTENNA SYSTEM.

a. General. The antenna system includes the stub-supported coaxial transmission line, the transmit-receive (T-R) switch, the radiating element with its paraboloidal reflector, and the rotating and tilting mechanisms (fig. 81). A single antenna is used for both transmitting and receiving, in order to conserve space, since this radar

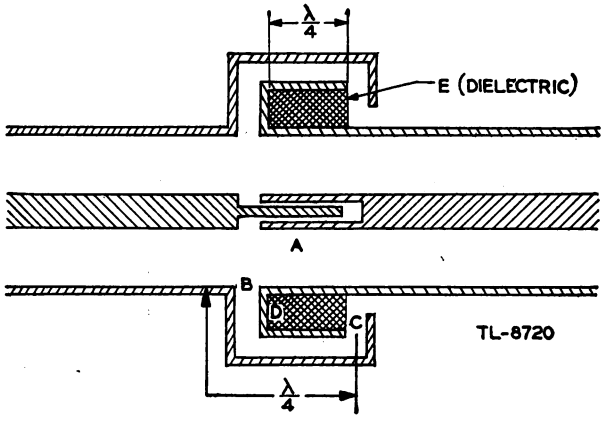

Figure 82. Detail of rotating joint.

set is to be installed in an airplane. A T-R switch is necessary to connect the antenna alternately to the transmitter and to the receiver, thereby preventing the sensitive receiver circuits from blocking during the transmitted pulse.

b. Feed lines. (1) The r-f transmission line is of the coaxial type, with a characteristic impedance of 50 ohms. The inner conductor is held in position by means of quarter-wave, short-circuited line sections, called *stubs*, which act as insulators. These supporting stubs are shown at points *B*.

(2) The method of matching the magnetron to the coaxial transmission line during oscillation is to use a quarter-wave transformer. The transformer, point *A*, is built into the output connection of the magnetron, and is adjusted in manufacture to give an output impedance of 50 ohms. Since there is no way to change the transformer, the magnetron is said to be pretuned.

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(3) The rotating joints at points E and F permit the antenna to be rotated and tilted freely. A detailed cross-section of a joint is shown in figure 82. The collars that are connected to the outer conductor of the line form an r-f choke, which in effect makes the outer conductor appear to be continuous. The two coaxial collars may be considered to be a section of transmission line. The distance from D to C is electrically a quarter-wavelength, although it is physically shorter than the free-space wavelength because of the increased capacitance introduced by the dielectric E. The short circuit at D is reflected to C as a high impedence. The distance from C to B is also a quarter-wavelength, so that the high impedance at C appears as a short circuit at B. Therefore a continuous conductor for the r-f energy appears to exist at point B, and one section of the line can turn freely relative to the other without appreciable loss of energy. The inner conductor

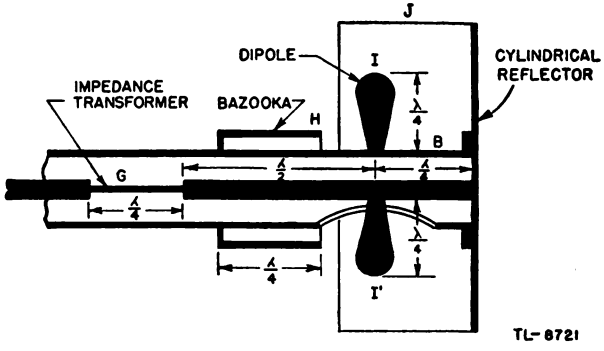

Figure 83. Detail of antenna.

appears continuous at point A because of the low capacitive reactance between the mating ends.

(4) The termination of the feed line is shown in the detailed sketch of the antenna in figure 83. The center conductor is short-circuited to the outer conductor at the cylindrical reflector J to provide mechanical support for the line. The dipole I-I' is mounted a quarter-wavelength away from this short circuit. A hole is cut in the outer conductor to permit connection of the element I' to the inner line. Bazooka H is used to isolate the grounded outer surface of the coaxial line from the element I. The feed-point impedance of the dipole is approximately 60 ohms. This impedance is reflected to transformer G by the half-wave section of line connected directly to the dipole. The transformer is a quarter-wave section of line whose characteristic impedance is changed to enable it to match the 50-ohm coaxial line to the 60-ohm antenna load.

c. T-R switch. (1) The T-R switch connects the transmitter to the antenna and disconnects the receiver during the transmitted pulse.

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It reverses these connections during the resting time while echoes are being received.

(2) Figure 84 shows the detail of the T-R switch used in this system. A type 721A switch tube is mounted in a cylindrical cavity to form the T-R switch. The tube contains two conical-shaped metal

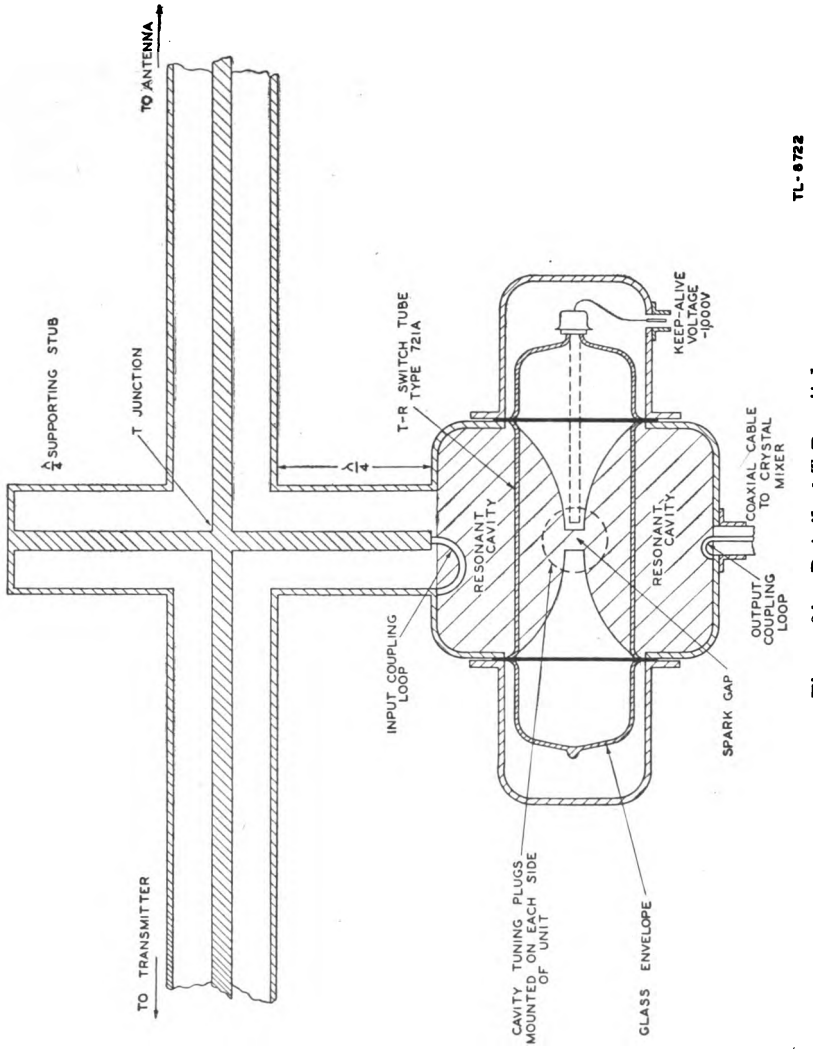

Figure 84. Detail of T-R switch.

electrodes which act as a spark gap. These are brought out through the glass envelope and connect to the cylindrical mount to complete the resonant cavity. The cavity, shown lightly cross-hatched, is at atmospheric pressure outside the glass envelope, but is partially evacuated inside the tube.

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(3) A simplified schematic sketch of the resonant cavity with an approximate equivalent circuit is shown in figure 85. The coupling loops which are used to couple *r-f* energy into and out of the cavity are represented as transformer windings. The resonant cavity is represented as two resonant circuits in parallel. If the gap at *A* does not break down, the input voltage is transformed to a high level by one tuned circuit and reduced to its original level in the secondary winding at the output. Thus the cavity acts as a highly selective transformer with a 1:1 turns ratio. If the input voltage is large enough, it is transformed to a voltage sufficient to break down the spark gap at *A*. When the gap conducts, the resonant tank is short-circuited, and a short circuit is therefore reflected into the input transformer primary.

(4) Although this conduction does not constitute a perfect short circuit, it causes a very low impedance to appear at the input coupling loop. This very low impedance reflects to the T-junction a quarter-

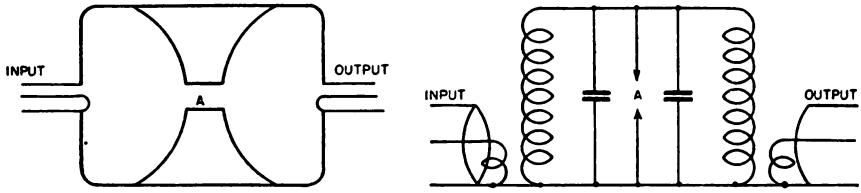

Figure 85. Equivalent circuit diagram of resonant cavity.

wavelength away as a high impedance. The circuit to the receiver therefore is disconnected by the conduction of the T-R switch tube.

(5) Since the impedance across the gap is not a perfect short circuit during the pulse, some energy from the transmitter is coupled into the receiver. The amplitude of the voltage so coupled is reduced by the T-R switch to a value which is low enough to prevent harm to the crystal mixer. An added safeguard is the *keep-alive voltage*. A constant negative potential of 1,000 volts is maintained on a third electrode near the break-down gap to facilitate ionization when the transmitted pulse is applied. This voltage keeps the vapor and gas within the tube very slightly ionized at all times.

(6) The receiver should be reconnected to the antenna as soon as possible after the end of the transmitted pulse so that echoes from nearby objects can be received. The speed with which this connection can be made is largely a function of the de-ionization time of the switch tube. The pressure of the water vapor or gas within the switch tube is selected to provide a low breakdown voltage and a short de-ionization time.

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(7) Echoes which return to the system find two paths in parallel at the T-junction. One path is a matched 50-ohm line through the T-R cavity to the receiver. The other is the coaxial line to the transmitter. Since the impedance looking into the magnetron when it is not oscillating is much less than when it is oscillating, standing waves exist on the line to the magnetron. To prevent loss of received signal, trombone *C* (fig. 81) is used to vary the length of the transmission line between the magnetron and the T-junction. The length of this section of line is adjusted to an odd number of quarter-wavelengths, so that the low output impedance of the magnetron reflects to the T-junction as a high impedance. Almost all of the echo signal is therefore directed into the 50-ohm path to the receiver.

d. Radiating system. (1) All of the output power from the transmitter is fed to a single dipole antenna. This dipole is made of two tapered elements which are each, electrically, a quarter-wave long

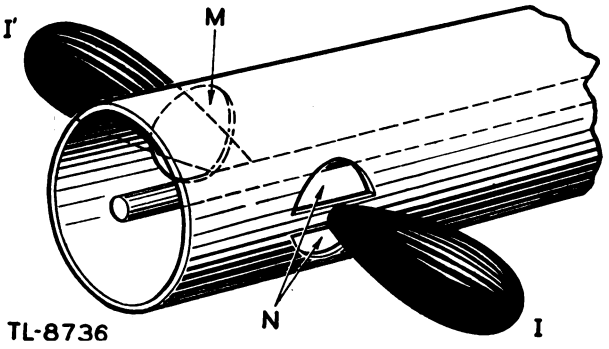

Figure 86. Detail of dipole mounting.

(fig. 83). This type of dipole has a broader frequency response than the usual thin antenna element, in order that small frequency changes may be tolerated.

(2) One-half of the dipole, *I'*, is connected to the center conductor of the coaxial line through a hole cut in the outer conductor (fig. 86). The other dipole, *I*, is connected to the outer conductor at the same position along the line. The energy on the coaxial line is conducted on the outer skin of the inner conductor and the inner skin of the outer conductor. In the absence of the holes indicated at *N*, the energy to excite element *I* would have to travel from the inside of the outer conductor out through hole *M* and around the outside of the outer conductor to the element. This extra distance would cause element *I* to be more than 180° out of phase with element *I'*, and the radiating system would be unbalanced. Although this unbalance may be used very profitably in some applications to produce a type of lobe switching, it is undesirable in this system. Therefore, holes *N* are cut in the

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outer conductor so that I and I' may be excited 180° out of phase. Element I may now be excited directly from the inside of the outer conductor by the energy which flows through holes N.

(3) The dipole antenna is mounted a quarter-wavelength from the cylindrical metal reflector. This combination is placed at the focus of a paraboloidal reflector with a 29-inch diameter, and it is used to direct the radiated energy into the paraboloid. The paraboloid concentrates the radiated energy into a beam which is approximately 10° wide.

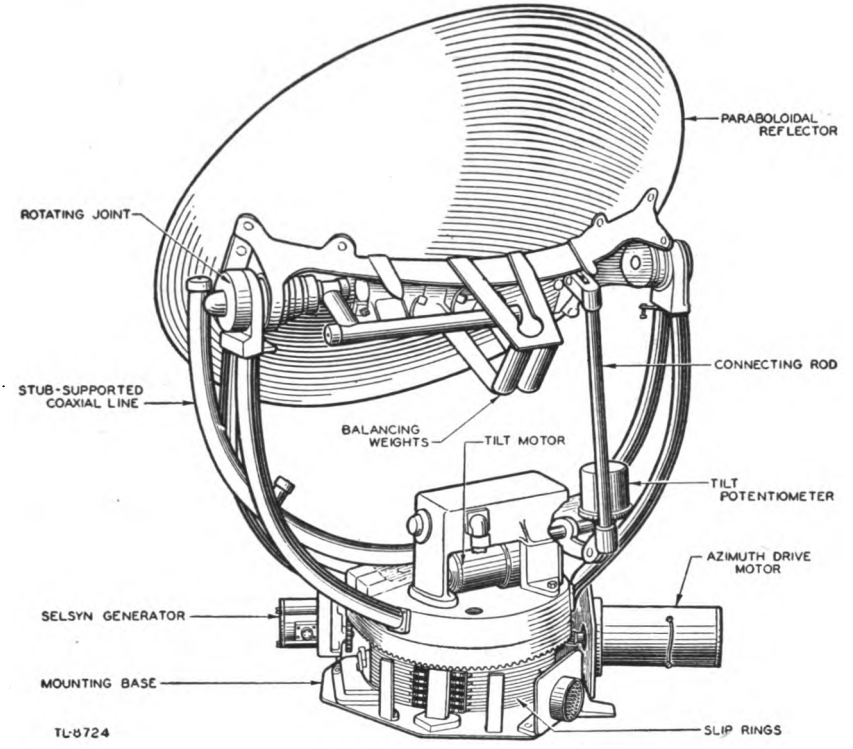

Figure 87. Spinner assembly.

(4) In the normal attitude of the aircraft in flight, the dipole is mounted parallel to the surface of the earth. The radiated energy is therefore horizontally polarized.

e. Rotating mechanism. (1) A sketch of the spinner assembly and the base on which it is mounted is shown in figure 87. The view shows the rear of the paraboloid in order to make clear the physical relationship of the tilting mechanism to the spinner. The guard plates around the mounting base are removed to show the position of the slip rings and the mechanism for driving the antenna in azimuth.

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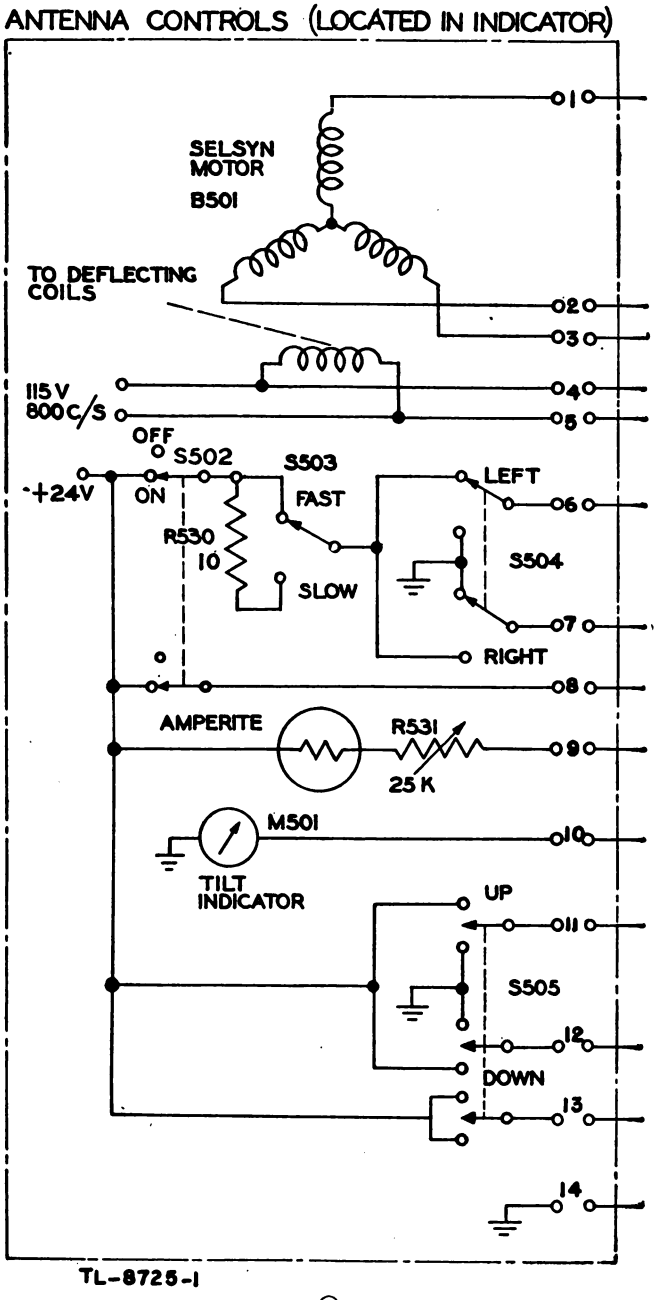

①

Figure 88. Schematic circuit

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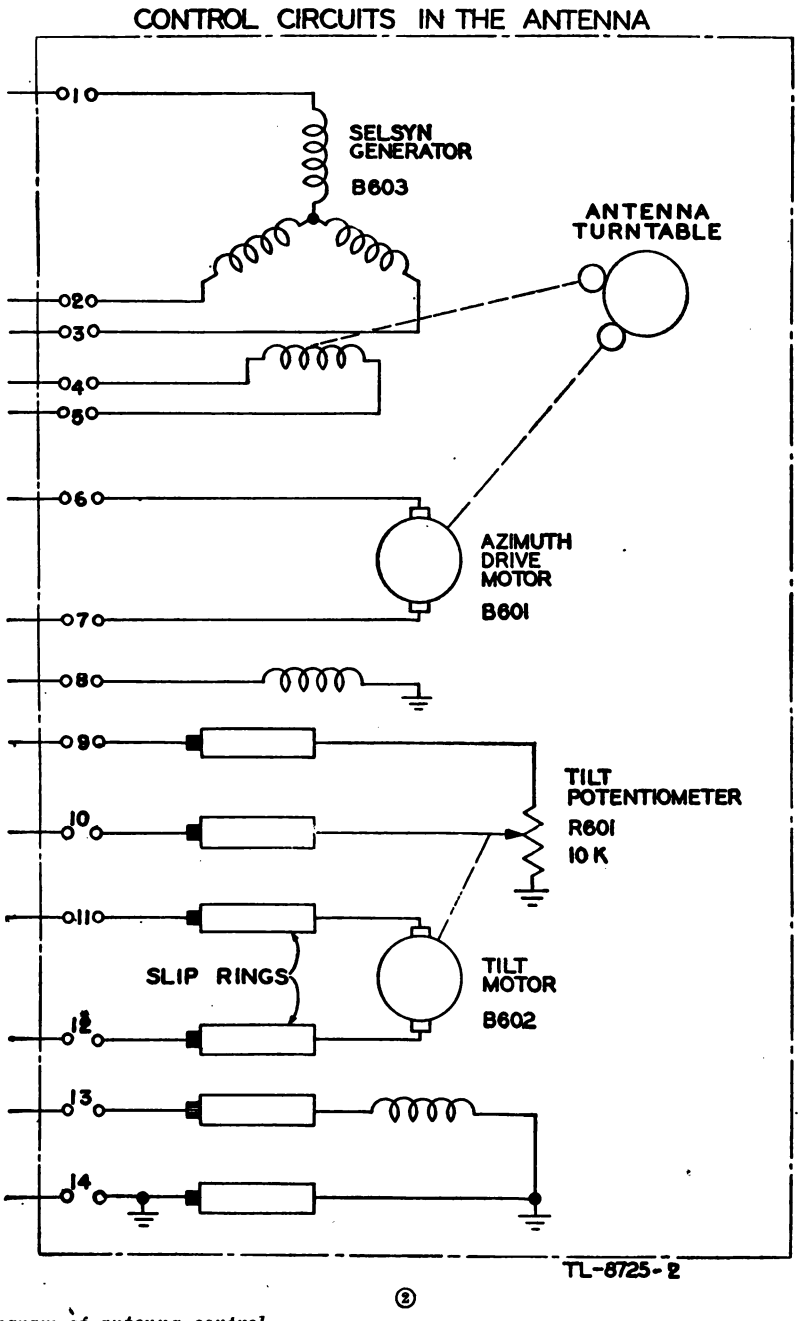

diagram of antenna control.

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(2) The spinner is rotated by the 24-volt, d-c azimuth drive motor. The pinion on the shaft of this motor engages a ring gear on which the spinner is mounted. A second pinion which engages the same ring gear drives the rotor of a selsyn generator. The voltages which are induced in the stator of the selsyn are fed to the stator of a similar machine, a selsyn motor, which turns the deflecting coils in the indicator. The currents that are set up in the stator windings of this selsyn motor produces a field which causes the rotor of the motor to align itself with the field. The rotor of the motor is always in step with the rotor of the generator, so that the sweep line on the indicator is always in step with the antenna.

(3) The spinner may be tilted a maximum of 20° above or below the horizontal by operation of the tilt motor. Since this motor with its speed-reduction gears is mounted on the rotating structure, the spinner may be tilted while it is rotating in azimuth. The tilting is accomplished by a connecting rod which is fastened to the paraboloid and driven by a crank keyed to the reduction gear shift. A potentiometer is geared to this same shaft to provide an indication of the angle of tilt of the spinner.

(4) The antenna control circuits are shown in figure 88. Operation of switch S503 in the indicator permits the spinner to be rotated at either 10 or 20 revolutions per minute. The slow speed may be used in conjunction with the direction-control switch, S504, to search over a small sector when one target area is to be investigated more closely than the normal PPI allows. Usually the switches are set so that the antenna rotates at 20 revolutions per minute in the clockwise direction to provide a normal PPI indication.

(5) The tilt motor, B602, may be turned in either direction by operation of tilt switch S505. This switch normally is open, and it can remain closed only as long as the operator holds it closed. The voltage tapped off the tilt potentiometer, R601, is fed to tilt meter M501 in the indicator. The voltmeter scale is graduated in degrees of tilt, so that the operator has a constant indication of antenna position before him. The amperite ballast tube is used to stabilize the current flowing through the tilt potentiometer. Resistor R531 is used to calibrate the tilt indicator by adjusting the total voltage that appears across R601 in the antenna assembly. Note that a common ground bus is carried through from the indicator to the antenna, and that both the rotating and the fixed parts of the antenna assembly have a common ground through a slip ring.

25. RECEIVER.

a. General. (1) The ultra-high-frequency superheterodyne receiver used here is of the conventional wide band design intended for pulse reception. The receiver components consist of a klystron

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local oscillator, a crystal mixer mounted in a resonant cavity, six stages of intermediate-frequency amplifiers, a diode detector, a video amplifier, a cathode follower, and the necessary regulated and unregulated power supplies. The relative distribution of these components is shown in figure 89, while the complete schematic circuit diagram is shown in figure 94. The main features of its operation are high gain combined with high signal-to-noise ratio, short recovery time, ease of adjustment, and use of a separate mixer-preamplifier section ahead of the main unit. This latter feature allows the mixer stage to be located close to the antenna and the receiver-output stage to be located close to the indicator.

(2) At a frequency of 3,000 megacycles per second, tubes may not be capable of amplification because of interelectrode capacitance. Likewise the transit time for an electron from cathode to plate is an appreciable part of an r-f cycle. At this frequency the period of one oscillation is approximately one-fifth of the electron transit time for elements 1 centimeter apart and with 100 volts across them, whereas at a much lower frequency the period of one oscillation is very long compared to the same transit time. In order to reduce transit time to a negligible value compared to the period at high frequencies, small tubes, such as acorn tubes, are used. These are practical as amplifiers up to approximately 200 megacycles. Lighthouse tubes function as amplifiers up to approximately 2,500 megacycles. At frequencies beyond this range r-f amplifiers are impractical and a greater number of intermediate-frequency amplifiers are used in the receiver in order to obtain satisfactory performance.

(3) At 3,000 megacycles (10 centimeters) the echo pulse is fed directly to the mixer, in the absence of r-f amplifier stages. The mixer must be located as close to the antenna as possible in order to keep transmission line losses to a minimum. The position of the antenna is such, as a rule, that it is impractical to mount the entire receiver near the antenna. The mixer and local oscillator are placed in the immediate vicinity of the antenna in this system, in order to convert the weak echo signals to the intermediate frequency of 30 megacycles before they are attenuated appreciably by the transmission line. The first two stages of i-f amplification follow immediately as a preamplifier to prevent the i-f signal from being lost because of the attenuation of the coaxial feed line to the remotely located receiver chassis.

(4) In radar, the received signal is of very small amplitude, usually in the neighborhood of a few microvolts. Therefore the receiver must have a very high gain. Because of the low amplitude of the echo pulse, a high signal-to-noise ratio must be maintained so that weak echoes are not obscured by internally generated noise.

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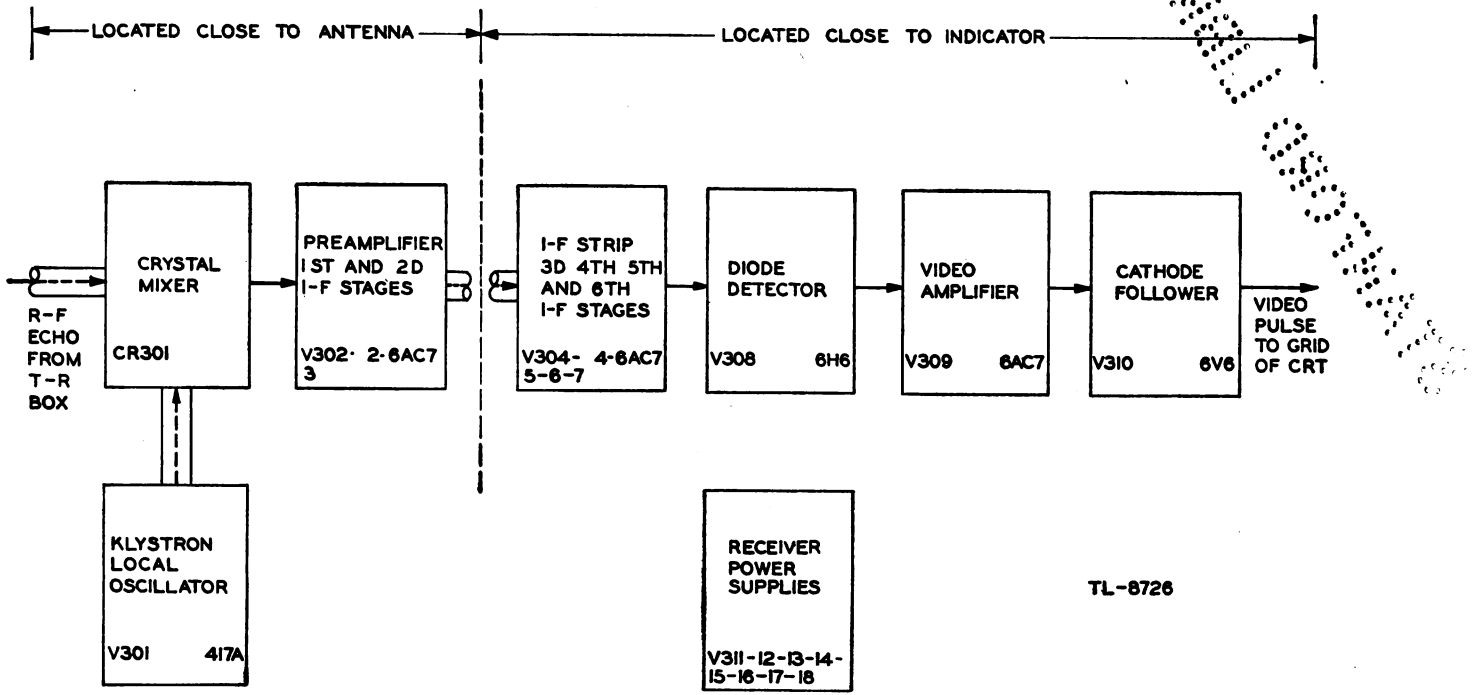

Figure 89. Block diagram of receiver.

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(5) In selecting the band width of the receiver several factors must be taken into consideration, chiefly the shape of the video pulse sent to the indicator and the response to weak echoes which may be lost in noise. The former factor calls for a wide band response, while the latter favors a narrow band response. The problem of compromising between these contradictory factors is best studied with a receiver which has a fixed signal-to-noise ratio at the mixer and a variable band width.

(6) Figure 90① shows the output of a receiver with wide band response displayed on a type *A* scope. The pulse shape is faithfully reproduced, but the noise is equal to the signal in amplitude. Such a wide band response is applicable to a fire-control unit in which a sharp leading edge is important for accurate range determination.

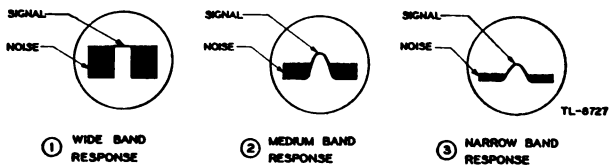

Figure 90. Effect of receiver band widths in pulse reception.

(7) Figure 90③ shows the output obtained when the same signal is fed through a receiver with narrow band response. The pulse is considerably distorted and has smaller amplitude, but the noise is reduced well below the signal level. Since a much weaker signal can be recognized in the noise, the receiver with narrow band response is effective for extremely long range warning systems.

(8) Figure 90② shows a compromise selection between preservation of the echo pulse shape and reduction of the noise level, which produces both reasonable pulse shape and signal-to-noise ratio on the indicator screen. In order to receive and to reproduce satisfactorily rectangular pulses equal in amplitude to the noise voltage, the receiver band width in cycles per second should be approximately 2, divided by the pulse width in seconds. For optimum conditions in practice, 1 megacycle per second is added to the band width to accomodate frequency drifts in either magnetron or local oscillator. In this system a pulse width of 2 microseconds is developed in the transmitting unit, and the receiver band width is established at 2 megacycles. Thus:

$$\text{Band width} = \frac{2}{2\text{x}10^{-6}} + 1\ mc/s = 1\ mc/s + 1\ mc/s = 2\ mc/s.$$

b. Klystron local oscillator. (1) The operating range of the reflex klystron employed as a local oscillator in this equipment is from 5.0 to 11.0 centimeters. In this application, however, only a small

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portion of the frequency range is utilized in adjusting the tuning of the receiver.

(2) The klystron, V301 (fig. 94), supplies a signal voltage to the crystal mixer 30 megacycles lower in frequency than the incoming signal. The tube consists of an indirectly heated cathode, a control grid, a resonant cavity with its grids, and a repeller electrode. The operation of the klystron is based on velocity modulation, in which the transit time between resonator and repeller is utilized. This principle is discussed in section XII, TM 11-466 and Navships 900,016. Whether or not oscillations occur depends on the phrase of the reflected electrons when they pass between the resonator grids. This phase is determined by the resonant frequency of the cavity, the accelerating voltage, and the reflector voltage. Because these variables are interrelated, oscillations may be obtained by adjustment of any one of them.

(3) Rough adjustment of the klystron frequency is obtained by tuning the resonant cavity with the threaded plug. Fine tuning over the desired portion of the frequency range is obtained by adjusting the repeller voltage by means of receiver tuning potentiometer R304 located on the front panel of the receiver chassis.

(4) The accelerating voltage between the cathode and the grounded cavity is fixed at −400 volts. The control grid potential is also fixed, and is the difference between the cathode voltage and the voltage drop across resistor R305. This potential is between 10 and 20 volts. Oscillation of the klystron is indicated by the crystal current meter, M301. When the klystron is operating the crystal current should be about 0.3 milliampere.

c. Crystal mixer. (1) The mixer is the main source of noise, unless preceded by r-f amplifiers, since it is the input stage. Types of mixers available at 3,000 megacycles usually have a gain of one or less, and therefore the selection is based primarily on the output noise level. The silicon crystal is used since it has about the lowest noise output, even though its gain is less than unity.

(2) The signals to be mixed are applied to the crystal mixer by a resonant cavity, which is used in place of a conventional tuned circuit. The cavity is practical in size at the frequency used in this radar system, and has the advantage of very low losses as compared to its equivalent tuned circuit. Figure 91 shows the equivalent circuit diagram of the crystal mixer. The mixing cavity is represented as the inductor L, tuned to the signal frequency b ythe capacitor C_p. Physically C_p is the screw plug in the side of the resonant cavity.

(3) The output of local oscillator V301 differs in frequency from the received signal by 30 megacycles. This output and the received signal are combined by the mixer to produce a current which contains

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several frequency components. These components include frequencies of the received and local oscillator signals, their higher harmonics, and their sum and difference. The difference frequency is selected as the intermediate frequency of 30 megacycles, and is fed to the first i-f amplifier, V302.

(4) Probe C_o couples the local oscillator signal into the mixer cavity and is adjusted so that the crystal current, as read on crystal current meter M301, is approximately 0.3 milliamperes. Final matching is accomplished by adjusting C_p and C_s, the probe which couples the sig-

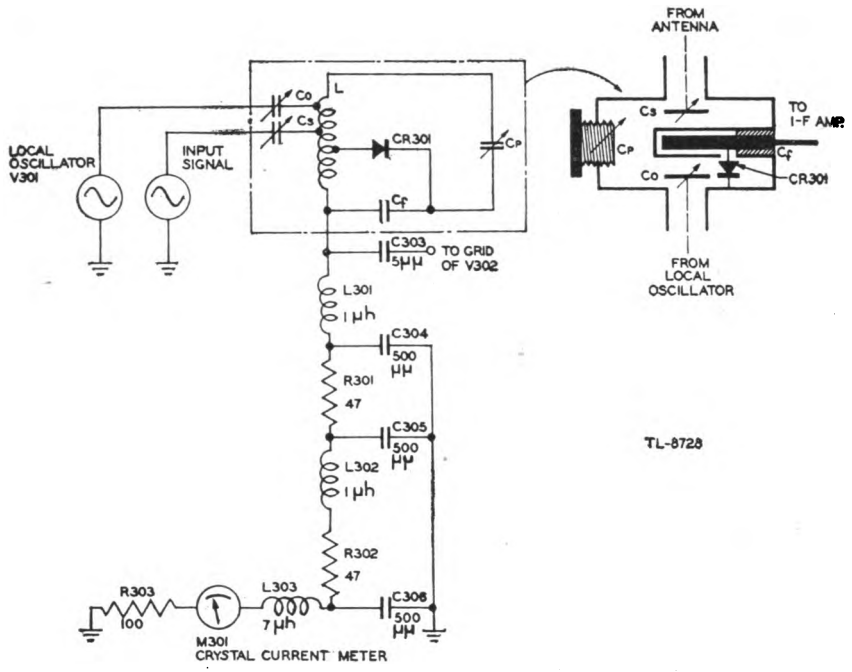

Figure 91. Equivalent circuit diagram of crystal mixer.

nal input from the antenna into the mixer cavity. C_s is set so that maximum echo signal is injected into the cavity.

(5) The i-f signal generated in the crystal is brought out by a lead from the base of the cavity. The high-frequency components are bypassed by means of filter capacitor C_f, which is built into the base of the cavity. The circuit elements L301, C304, R301, C305, L302, R302, and C306, which form a three-stage, L-type filter, serve to filter the intermediate frequency out of the circuit of the crystal current meter.

d. Intermediate-frequency stages. (1) The i-f section of the receiver includes six amplifier stages (fig. 94). The first and second stages are employed as preamplifiers and are located with the

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mixer and local oscillator in the immediate vicinity of the antenna. The remaining stages are located in the receiver chassis along with the detector, video amplifier, and cathode follower. All i-f stages are adjusted for maximum response at a center frequency of 30 megacycles and the tuning is broadened to give an over-all band pass of 2 megacycles.

(2) A simplified diagram of the i-f input circuit is shown in figure 91. Inductor L304 is tuned to resonate at 30 megacycles with its distributed capacitance, tube input capacitance, and capacitors C303 and C_f in series. The crystal mixer acts as a resistor shunted across capacitor C_f. Its reflected resistance loading the tuned circuit is

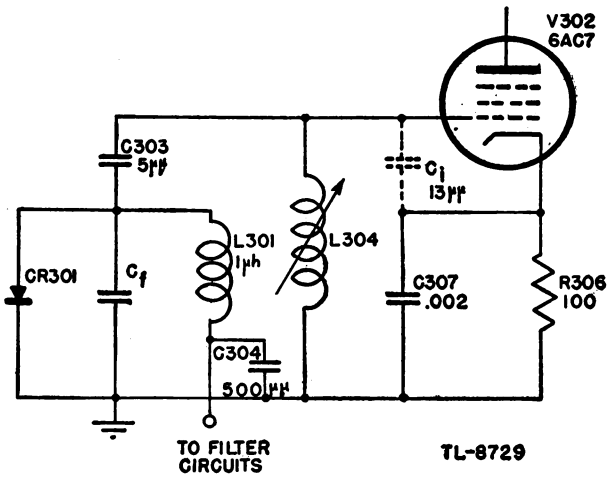

Figure 92. Schematic circuit diagram of intermediate-frequency input.

somewhat greater because of the step-up ratio of C_f to C303. The voltage applied to the grid of V302 is the crystal voltage stepped up several times.

(3) The two preamplifier stages (fig. 94) are conventional in operation. The interstage coupling network is a resonant circuit loaded by resistor R307 to broaden the response. The output circuit matches the low input impedance of the coaxial transmission line to the plate of tube V303. The circuit consists of the output capacitance of the tube in parallel with C313, inductor L306, and resistor R311, shunted by the impedance of the coaxial line. These elements can be considered as a resonant, step-down autotransformer. The transmission line transfers the i-f signals to the rest of the receiver, and is terminated in its proper load by resistor R313 and the tapped inductor L307.

(4) The i-f stages, V304, V305, V306, and V307, constitute an i-f strip which is inclosed in a metal box for shielding. The entire strip, including the shield, may be replaced easily. Since the tuning of the

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i-f inductances is not extremely critical, the replacement of individual tubes does not necessitate retuning of the i-f strip to secure proper receiver performance.

(5) The gain of the receiver is controlled by means of potentiometer R316 which regulates the plate and screen voltages of the third and fourth i-f amplifiers. This potentiometer control is brought out to the front of the receiver panel as the receiver gain control knob.

e. Detector. (1) The i-f signals of the i-f strip are converted to video-frequency signals by the type 6H6 double diode, V308, in order that they can be observed on the indicator screen. The two halves of the type 6H6 are connected in parallel so that the tube functions as a conventional diode detector.

(2) The intermediate frequency across the tuned circuit of L311 is applied between cathode and ground of the diode. The video current, which follows the amplitude fluctuations of the intermediate frequency, flows through diode rectifier V308, choke coil L312, and load resistor R329. The i-f component of the diode current is bypassed to ground by capacitor C329. The video signal, therefore, is a negative pulse appearing mainly across load resistor R329 and is applied to the grid of video amplifier V309 through capacitor C330.

f. Video amplifier. (1) L312 and C329 act as a filter to eliminate the i-f component of the rectified current from the video input circuit, and as a series compensation to improve the frequency response of the video amplifier.

(2) The midfrequency gain of the stage is approximately 35 and the band width between half-power points is 0.7 megacycle. The positive amplified video signals are developed across R333 and are applied to the cathode-follower input circuit through C334. Resistor R334 tends to prevent strong signals on the grid of V310 from charging C334.

g. Cathode follower. (1) The video pulses are delivered to the indicator grid by way of a cathode-follower stage. A beam-power tetrode V310, type 6V6, is used in this stage because it has a fairly high transconductance and a high current-carrying capacity.

(2) The voltage relationships in the cathode follower are shown in figure 93. The normal bias with no signal on the grid is approximately −20 volts. A maximum video signal of about +90 volts on the input of the cathode follower causes the plate current through the tube to increase from the no-signal level of 20 milliamperes to approximately 92 milliamperes, producing an output voltage of 72 volts and reducing the bias to 2 volts.

(3) An output impedance of approximately 200 ohms is realized which effectively minimizes pickup by the oscilloscope lead and reduces interstage coupling between the oscilloscope input circuit and

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the receiver circuits. In addition, the leading effect on the video amplifier is negligible, since the input impedance of the cathode follower is high because no grid current flows. The effective input capacitance between grid and ground is much smaller than that of the same tube used as an ordinary amplifier.

h. Power supply. (1) The required power supplies for the receiver circuits (fig. 94) are contained within the main receiver chassis with the exception of the filament voltages for tubes V301,

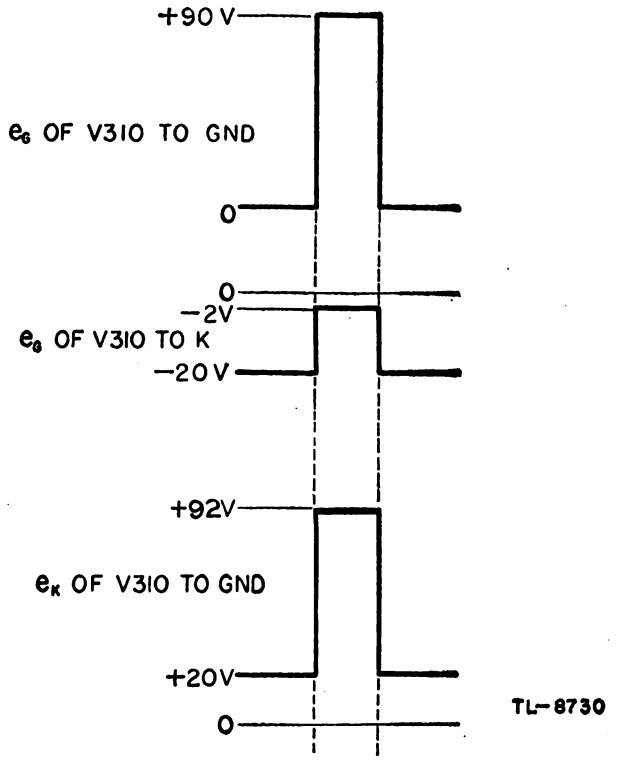

Figure 93. Voltage relations in cathode follower.

V302, and V303, for which filament transformer T301 is located near the preamplifier stages. All plate and screen voltages are regulated except the 200-volt supply furnished to the plates of V307, V309, and V310.

(2) A regulated source of negative potential is required for the cathode and repeller voltages of the local oscillator V301. Transformer T302 supplies plate and filament voltages for rectifer tubes V311 and V312 connected in a voltage-doubling circuit. The output of the rectifier is regulated by the two-stage inverse feedback circuit composed of V313 and V314, which eliminates output voltage fluc-

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tuations. The klystron is supplied with a regulated cathode potential of −400 volts and a regulated repeller potential which may be varied between −400 volts and −550 volts by controlling the resistance of R304. Filament voltages for other tubes in the receiver chassis are also furnished by this supply.

(3) Some tubes in the receiver unit are not critical with respect to regulation of plate supply. To supply them a heavy-duty power source is used, which also furnishes the regulated screen and plate voltages for the remaining receiver tubes which require some regulation. Transformer T303 supplies plate and filament voltages to the full-wave rectifier tubes V316 and V317, and the heater voltage for V314. The elements of V316 and V317 are connected in parallel to accommodate the high current requirement. The rectified output of these tubes is filtered and divided into two major components: +200 volts at about 300 milliamperes lead, and +105 volts regulated and supplying a load of about 75 milliamperes lead. This voltage is produced from the 200-volt source by the drop through R343, and it is held constant by regulator tube V318.

The klystron voltages and the screen and plate voltages for the two pre-amplifier tubes are carried by two cables connected to jacks J301 and J 302.

26. INDICATOR.

a. General. (1) The indicator for this radar system is of the PPI type, using an electromagnetic cathode-ray tube. The sweep signal which must be produced in order to cause a linear deflection of the electron beam is a saw-tooth current. The trace is swept radially from the center of the tube toward the outer edge along a line which shows the direction in which the antenna is pointing. In order to show this direction at all times, the trace on the cathode-ray tube screen and the antenna must rotate at exactly the same rate. One direct way to produce a rotating sweep is to use deflection coils which may be revolved around the cathode-ray tube.

(2) The antenna is driven by a motor at 20 revolutions per minute. As the antenna rotates, a selsyn generator which is geared to the antenna causes the rotor of a selsyn motor to assume the same relative angular position as the rotor of the generator. Then, as the antenna is rotated, the selsyn motor rotates at the same speed and exactly in step. The selsyn motor is used to drive the deflection coils around the cathode-ray tube.

(3) Generally the stators of the two selsyns are aligned so that the trace on the screen is vertical when the antenna is pointing dead ahead. If a scale is placed around the edge of the screen, the relative bearing of a target may be read directly.

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b. Sweep multivibrator. (1) This radar system is designed for general searching of an area 100,000 yards in radius. When the target comes close to the equipment, more accurate measurement of the range of the target is desired. For this reason, an additional scale to measure ranges from zero to 20,000 yards is included.

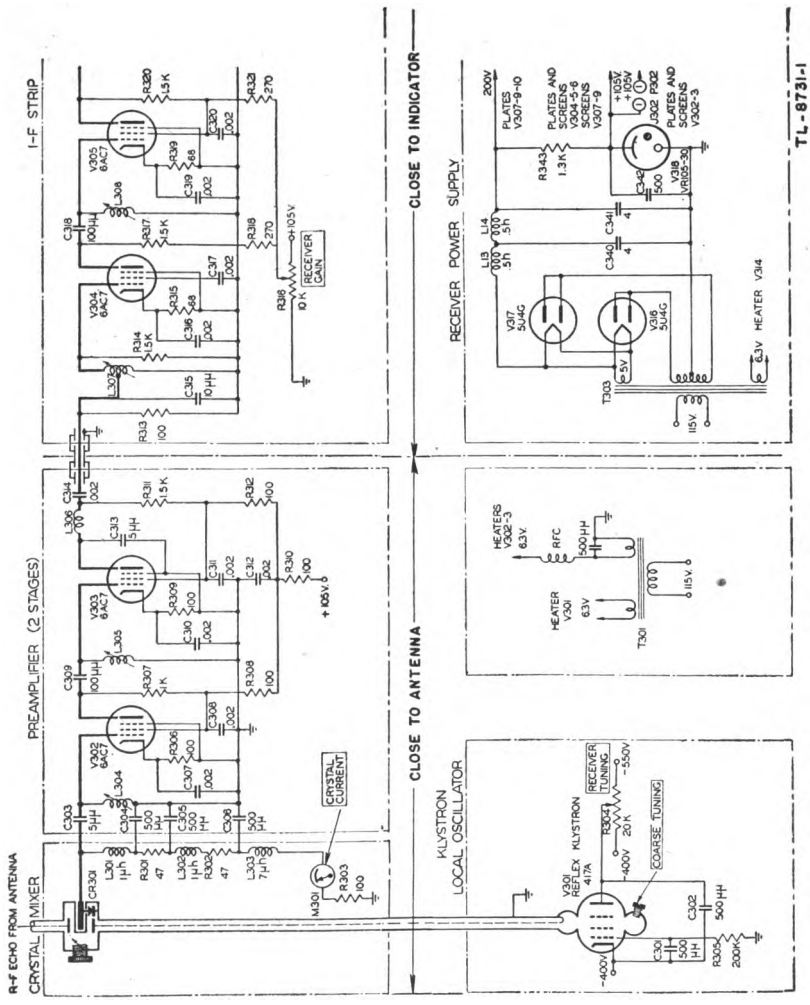

Figure 94. Schematic

(2) The time required for the radar pulse to travel out 100,000 yards, be reflected, and travel back the same distance to the receiver is approximately 610 microseconds. The time required for the pulse to travel out 20,000 yards and back is 122 microseconds. These times may be calculated readily from the constants given in section I. Since

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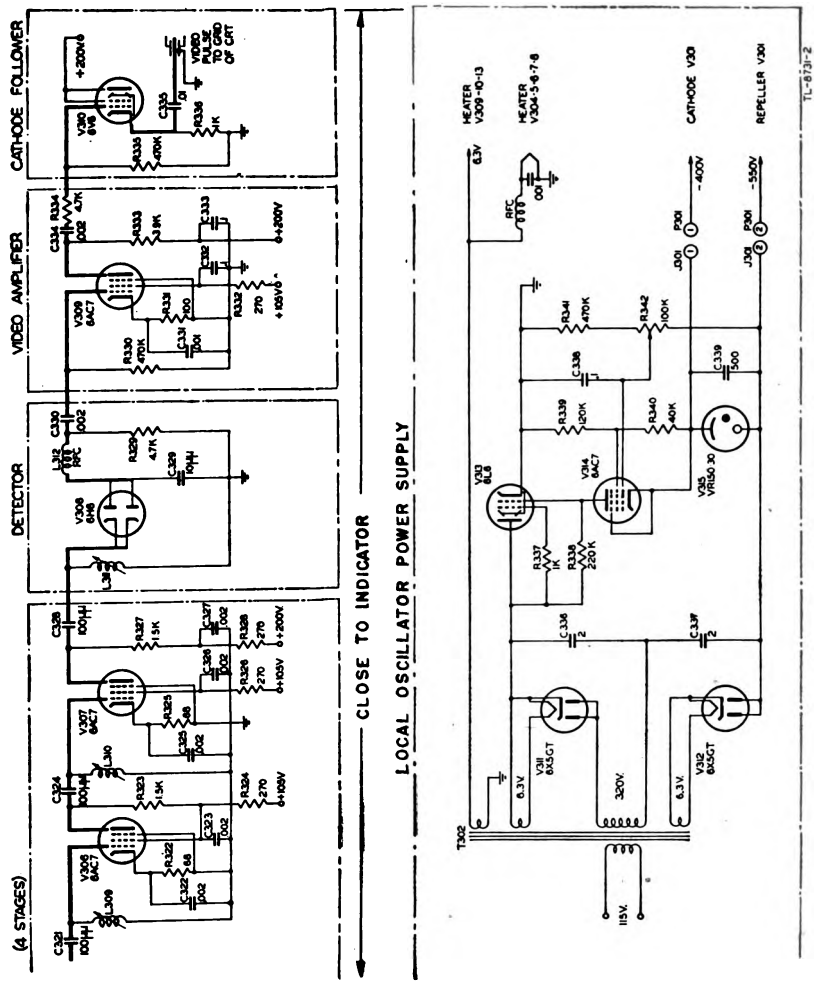
the radar indicator must show the distance from the radar equipment to the target, the current in the deflection coils must have a waveform that deflects the beam from the center of the tube to the outer edge in 610 microseconds for the long range, and in 122 microseconds for the short range.



② *circuit diagram of receiver.*

(3) The pulse-repetition frequency is 800 pulses per second, which means that there is an interval of 1,250 microseconds between pulses. In order to permit a long time for the current through the sweep coils to return to zero, it is desirable to limit the time of increase in the current which produces the sweep to the 610 microseconds required

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for the longest range. The remainder of the 1,250-microsecond period is used for the return trace.

(4) A multivibrator is used to control the duration of the sweep because it is capable of generating a pulse of exactly the proper duration at a rate which can be synchronized by the pulse from the timer. The type used in this indicator is a one-shot multivibrator, often called a *single kick* or a *start-stop* circuit. The one-shot variety can never get out of synchronism since it does not put out any signal until it is triggered. The circuit selected is one which is triggered by a negative pulse and from which a positive square pulse may be taken as output.

(5) The circuit of the sweep multivibrator is shown in figure 95 and the voltage waveforms are shown in figure 96. Tube V501 is normally conducting, since it is operated without bias. Under this condition, the plate current is about 8 milliamperes and causes a drop

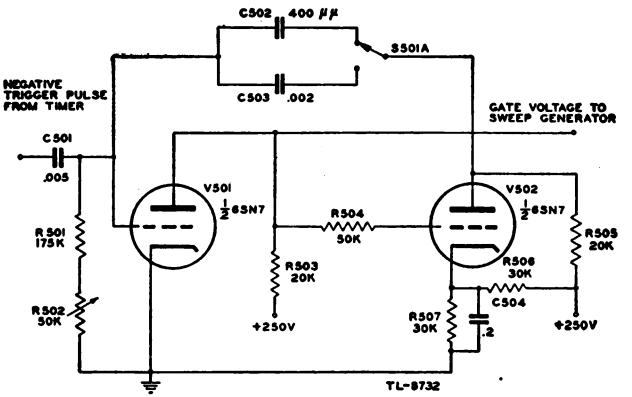

Figure 95. Schematic circuit diagram of sweep multivibrator.

across resistor R503 of 160 volts. The effective plate voltage of V501 thus is +90 volts. The grid voltage for tube V502 also is +90 volts, because of the direct coupling between the tubes. Resistor R504 is in series with the grid of the second tube to limit grid current to a safe value in the event of a positive signal with respect to cathode. The cathode of V502 is connected to a voltage divider, resistors R506 and R507, which places the cathode at approximately 125 volts above ground. The effective grid-to-cathode voltage when V501 is conducting is therefore −35 volts. This voltage is more than sufficient to cut off tube V502, which is thus normally nonconducting. The circuit remains inactive until an external signal is applied to it.

(6) The negative trigger pulse from the timer is coupled into the grid of V501 through capacitor C501. As a result the plate current of V501 is decreased, and the grid of V502 rises toward +250 volts. The cathode of V502 is held at a relatively constant potential by capacitor C504, so that the increased grid voltage causes the tube to

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conduct. The current flow through resistor R505 reduces the plate voltage across the tube and also the charging potential for capacitor C502 (or C503). C502 begins to discharge, setting up a negative voltage across resistors R501 and R502 in the grid circuit of tube V501. The effect is cumulative and practically instantaneous in cutting off tube V501 and in driving V502 to maximum plate current.

(7) Tube V501 remains cut off until C502 has discharged sufficiently to let the grid voltage of V501 return to a less negative value than cut-off. The voltage rises exponentially toward cut-off, as shown in figure 96①. When V501 begins to conduct, its plate voltage decreases. This decrease in turn lowers the plate current through

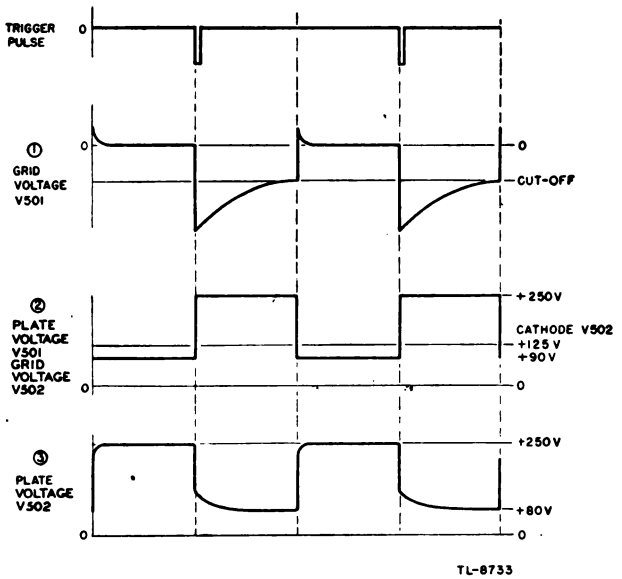

Figure 96. Waveforms in sweep multivibrator.

V502. The plate voltage of V502 rises and swings the grid of V501 positive, returning both tubes to their normal operating condition. The time between the turning off and turning on of V501 is controlled directly by the time constant of the circuit which includes the plate circuit of V502, capacitor C502 (or C503), and resistors R501 and R502. Switch S501A selects C502, a 400-micromicrofarad capacitor, for the 20,000-yard range, and C503, a capacitor five times as large, for the 100,000-yard range.

(8) The waveform of the signal at the plate of V501 is a good square wave the start of which is controlled by the input trigger pulse. The duration of the positive half of the square wave is accurately set to either of two values by the selector switch S501A, and can be corrected for minor changes by resistor R502. This square wave is

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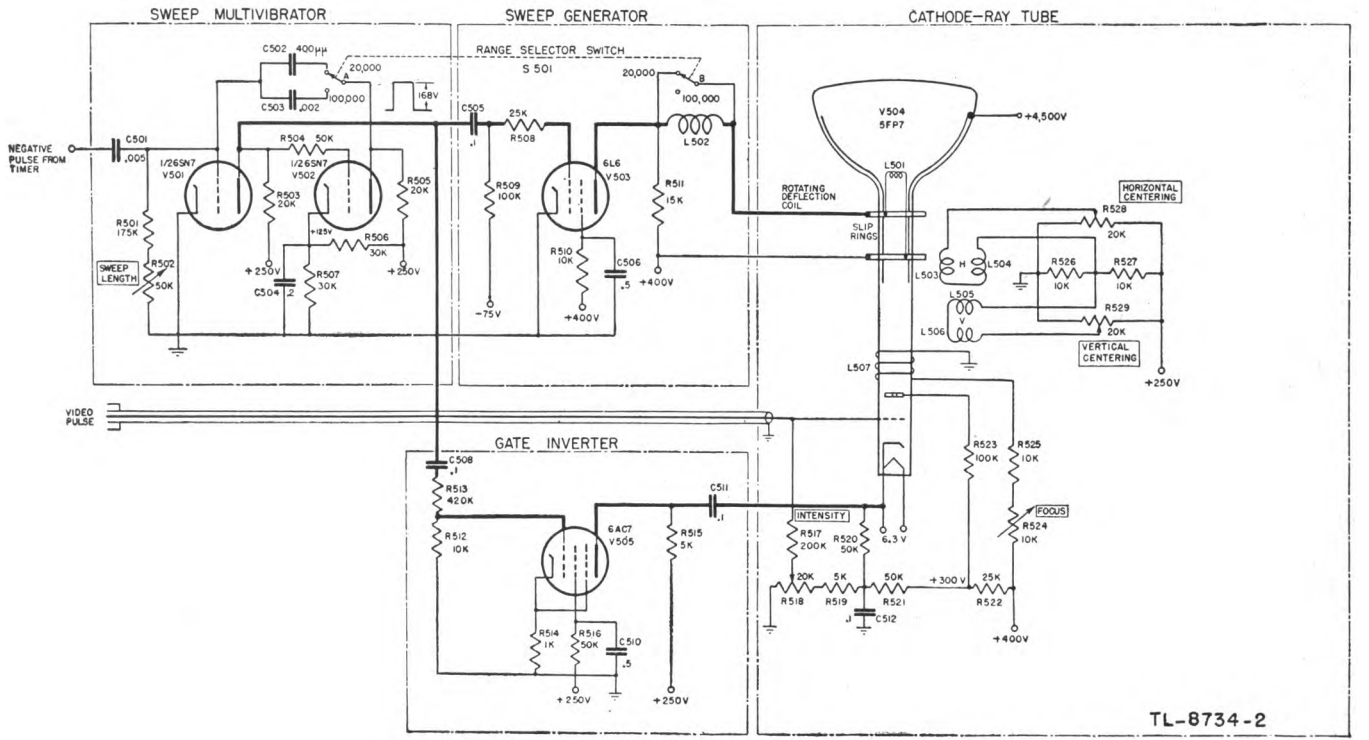

① *Schematic circuit diagram of PP1 type indicator.*

Figure 97.

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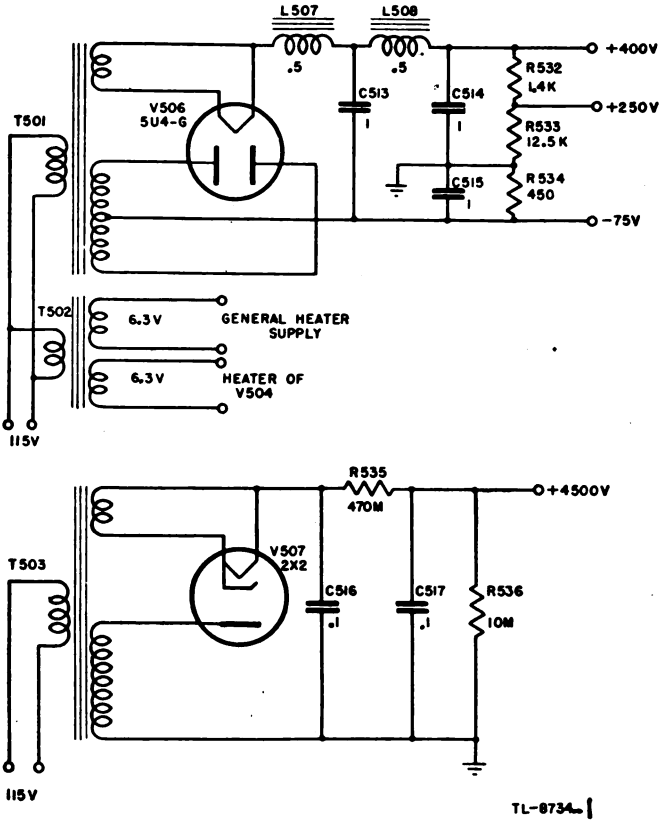
applied to the sweep-generator tube V503 to control the time of rise of the sweep current.

c. Sweep generator. (1) The circuit used to generate a saw-tooth current in the deflection coils is shown as part of the complete circuit diagram of the indicator in figure 97, and is similar to that described in section IX, TM 11–466 and Navships 900,016. The current in a circuit consisting of inductance and resistance in series builds



② *Power supplies for PPI indicator.*

Figure 97—Continued.

up toward a maximum value along an exponential curve. The maximum is determined by the applied voltage and the constants of the circuit. The first part of the exponential curve, which is very nearly linear, is to be used as the sweep. Since two sweep speeds are desired, the inductor L502 is used to limit the rise of current to that which is just sufficient to deflect the beam linearly from the center of the screen to the outer edge in 610 microseconds. The current through the deflection coil must build up to the same magnitude for the short range, in

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order that the beam will be deflected to the edge of the screen, but the rate of rise of current must be five times greater since the current must rise to this value in 122 microseconds instead of 610. The rate of rise is made faster by switch S501B, which short-circuits L502. The effective inductance and resistance in the circuit are reduced and the current can build up more quickly.

(2) Tube V503 is normally cut off by the −75-volt bias applied to the grid. This tube acts as a switch. It is turned on by the leading edge of the positive pulse from the multivibrator, and it is turned off by the trailing edge. Tube V503 must offer about the same resistance to the flow of electrons at all times during the conducting period if the sweep is to be linear. The grid voltage therefore must not change during this time. The time constant of the input circuit, C505 and R509, is made long relative to the duration of the positive pulse by adding resistor R508 to limit grid current, so that the charge on C505 does not change greatly during the conducting period.

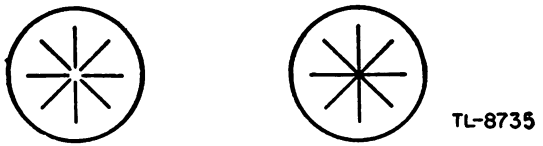

Figure 98. Effect on PPI indicator of failure of current in deflection coils to fall to zero.

(3) A beam-power tube, V503, is used as the switch tube because a large current is required for the sweep. The tube can be cut off by cathode bias, but the resistance between cathode and ground should be less than 1,000 ohms, so that the build-up of current in the deflection coil may be just as linear as possible during the conducting period. The cut-off bias is therefore supplied by applying a negative voltage to the grid.

(4) The current in the deflecting coil must be reduced to zero at the end of each sweep so that the spot may return to the center of the screen. If the current does not fall to zero, the electron beam never quite returns to the center of the screen, and a small circle appears there (fig. 98).

(5) When V503 is cut off, the conduction in both the tube and in the deflection coil must stop suddenly. The energy in the magnetic field of the deflection coil is dissipated in the damping resistor R511. Some oscillations in the deflection coil may be caused by the shock of interrupting the current, but these do not affect the appearance of

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the screen because the intensity of the trace is reduced at the end of the sweep.

d. Gate inverter. (1) The method of eliminating any trace on the oscilloscope except that produced during the actual sweep time is to bias the cathode-ray tube beyond cut-off. A gate is then applied which permits the tube to trace the signals. In this indicator the output of the receiver is used to turn on the electron beam, and therefore the gate need only bring the bias to the point where small signals can control the intensity of the trace.

(2) The output of the multivibrator is attenuated and inverted to produce the gate for intensifying the indicator tube. The circuit which couples gate-inverter tube V505 to tube V501 acts as an isolation network to prevent distortion of the waveform at the plate of V501. The time constant of the network is made large to prevent distortion of the square wave when it is applied to the grid of V505. In addition to isolating the inverter tube from the multivibrator, resistors R512 and R513 form a voltage divider to reduce the signal by a ratio of 42 to 1.

(3) The gate inverter uses a type 6AC7 pentode as a degenerative amplifier, with resistor R514 unbypassed, to preserve the waveform. The plate load resistor R515 is purposely small to provide a relatively low output. The gate is a square-wave voltage of about 20 volts, the negative portion of which corresponds in time to the sweep.

e. Cathode-ray tube. (1) The indication of the range and relative bearing of the target appears in this radar set on the screen of an electromagnetically focused and deflected cathode-ray tube. The electron beam is focused to a small spot on the screen by means of the magnetic field set up within the tube by the current in coil L507. The strength of the field can be varied by potentiometer R524, since this resistance controls the amount of current in the coils.

(2) The beam in most cathode-ray tubes strikes the center of the screen when no deflecting field acts on it. However, slight inaccuracies in manufacture can cause the beam to strike a small distance away from the center. It is usual, therefore, to provide two pairs of centering coils to correct the effect of improper alignment of the elements within the tube. The arrangement shown in figure 97 enables the current in the coil to be controlled in both magnitude and direction so that the spot may be moved to any part of the screen.

(3) The bias on the grid of the cathode-ray tube is adjusted so that electrons cannot flow in the beam. During the actual time of the sweep the potential of the cathode is lowered by the gate pulse, but the effective bias is still large enough to prevent the appearance of a trace on the screen. The output from the video amplifier in the receiver is a series of positive pulses which are applied to the grid.

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Each pulse causes a spot of light to appear on the screen, so that the range and relative bearing of the target is indicated by the position of the bright spot on the cathode-ray tube. Any signals which come between the end of one sweep and the beginning of the following sweep do not appear on the screen, since the tube is biased well beyond cut-off in the absence of the gate pulse.

f. Power supply. (1) The power supply for the indicator is conventional. Because an electromagnetic cathode-ray tube is used in the indicator a relatively large current is required for the focusing and positioning coils.

(2) A single type 5U4–G tube, V506, is used in a full-wave rectifier circuit to supply +400 volts, +250 volts, and −75 volts. The 800-cycle line voltage is stepped up by transformer T501 and is rectified by the full-wave rectifier tube, V506. The output is filtered by L507, C513, and L508. Resistors R532, R533, and R534 serve as bleeder resistors and as a voltage divider to provide +250 volts for use in both the indicator and the timer. A negative voltage is provided by grounding the voltage divider at the junction of R533 and R534. Capacitors C514 and C515 are used to stabilize the output voltages.

(3) The accelerating voltage for cathode-ray tube V504 is supplied by the half-wave rectifier circuit composed of T503 and V507. Since the current drain of the cathode-ray tube is very small, the simple *R–C* filter is adequate and economical. Note that a positive accelerating voltage is applied to the aquadag second anode in the electromagnetic cathode-ray tube. In the electrostatic tube discussed in section III the accelerating voltage was a negative voltage applied to the cathode in order that the second anode and deflection plates might be grounded.

(4) Because the cathode of cathode-ray tube V504 is not grounded, a separate heater transformer winding is provided on T502 for this tube. The other secondary winding on T502 is used to supply 6.3 volts to all tubes in the system which require this heater voltage.

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Section V
Timers

27. GENERAL.

a. Introduction. (1) Circuits which control and synchronize the operation of the various components of radar equipments are known as *timers*. The timing circuits are either assembled into a unit which constitutes a separate component of the equipment, or, as in the usual case, they are contained within one or more additional components, such as the indicator, the receiver, and control circuits.

(2) For the purposes of study, timers have been divided into two general types. One is the self-synchronized type in which the timing function is performed within the transmitter circuits. The other is the externally synchronized type in which a master oscillator in the timer establishes the repetition rate and supplies trigger voltages for controlling the entire system.

b. Timing signals. (1) The signals required of the timing circuit depend largely upon the purpose of the set, the type of transmitter, and the method of data presentation. Typical requirements are illustrated in figure 99. This diagram does not necessarily apply to any particular set, but shows the more common timing pulse channels in general use in many systems. In figure 100 these timing pulses are shown in their proper time relationship.

(2) Figure 100 represents the time-reference pulse originating in the timer circuit, and shows wave forms typical of the externally synchronized systems. This figure is equally typical of self-synchronized systems in which the time-reference pulse is developed in the transmitter circuit. The time-reference pulse is used to trigger the various timing circuits into operation. Thus, in the former case, the pulse shown in figure 100① becomes a transmitter trigger, and in the latter case it becomes a timer trigger. In either case it serves as the reference point from which the other operations are timed.

(3) The second timing pulse shown in figure 100③ gates the receiver to make it operative during only the proper portion of the pulse cycle. It may be necessary to gate the receiver in this way in some sets in which short minimum ranges are important. The T-R switch normally limits the amount of transmitter signal entering the receiver

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to a value which does not damage the crystal mixer, but it may not prevent blocking of the receiver circuits. When blocking occurs, the receiver remains inoperative for an interval immediately following the transmission of the pulse. This interval is required for recovery of the receiver to a state of normal sensitivity. If the plate and screen voltages of the first two or three i-f stages are removed during the transmitting time, receiver blocking is prevented and the minimum range at which targets can be detected becomes simply a function of the pulse width. The timing circuits are made to apply these screen and plate potentials in the form of a positive rectangular gate voltage

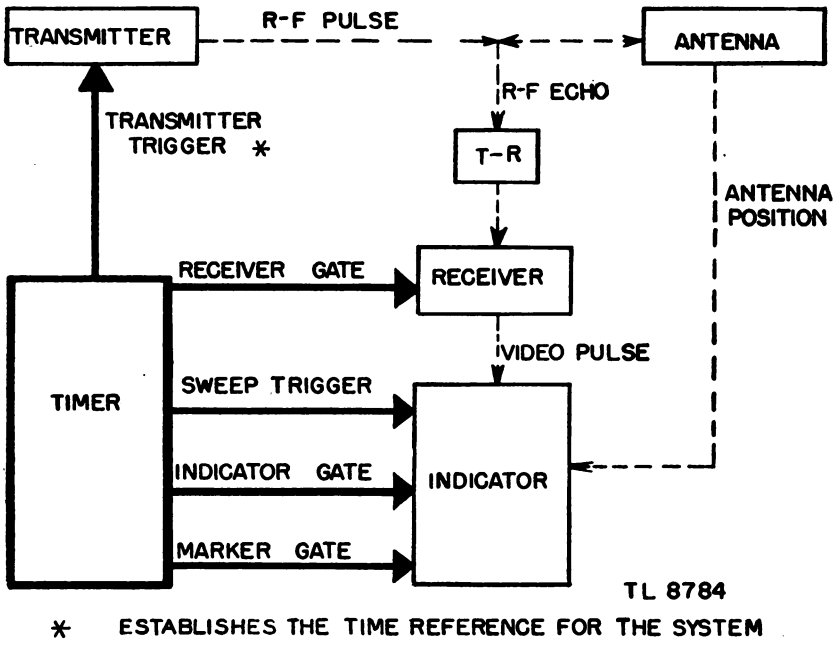

Figure 99. Typical timing pulses of a radar timer.

during the time interval beginning just after the end of the transmitted pulse and ending after echoes are received from the most distant targets in the operating range. Improvements in radar-receiver and T-R switch design have shortened recovery time to such an extent that, in many recent sets, it is unnecessary to gate the receiver.

(4) The timer starts the range sweep in the indicator circuits. The timing pulse may be in the form of a trigger, as shown in figure 100④, where it occurs simultaneously with the transmitter trigger, so that the beginning of the sweep and the beginning of the transmitter pulse coincide. If any appreciable delay occurs in starting the sweep in a cathode-ray tube which uses magnetic deflection, the sweep trigger may be made to precede the transmitter

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trigger to compensate for this inherent delay. The more commonly encountered alternative, however, is to trigger the sweep coincidently with the transmitter and develop a trapezoidal sweep voltage to overcome the delay.

(5) If the tube remains in an operating condition during the entire pulse period, both the forward sweep and the return trace will be

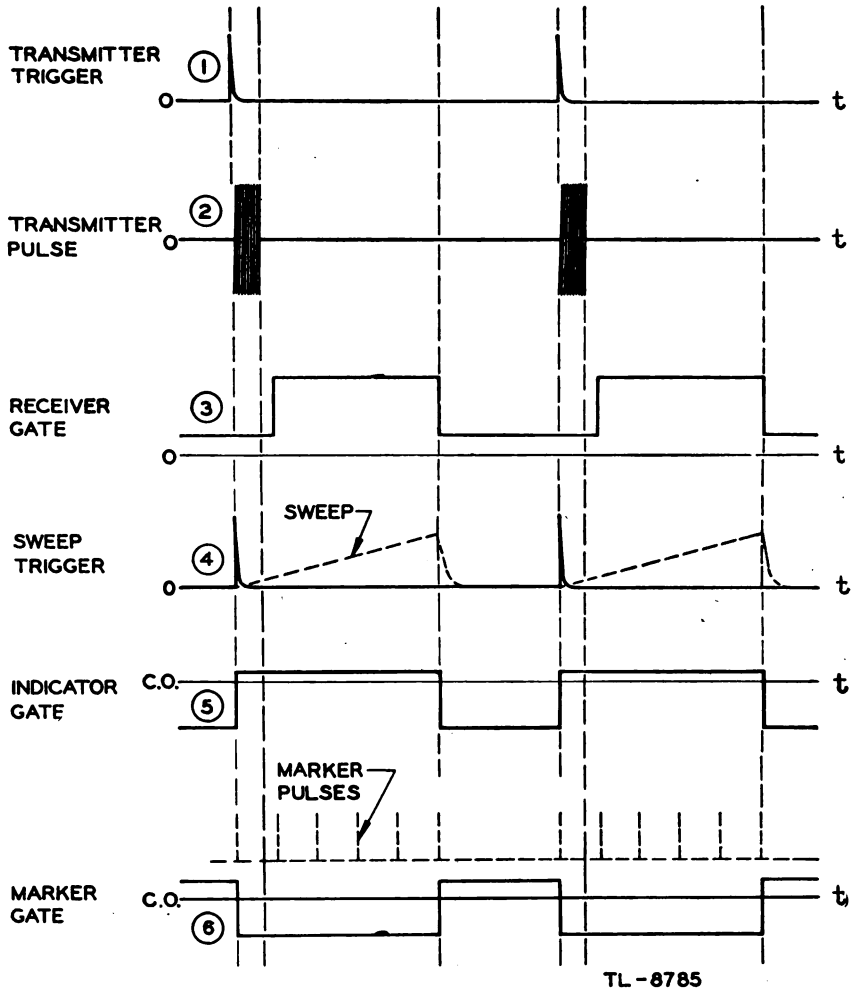

Figure 100. Time relationship of pulses furnished by timer shown in figure 99.

visible, so that signals appearing on the screen from targets outside the desired range will cause confusion in interpretation of echoes. To avoid this, the circuits of the cathode-ray tube permit its operation to be controlled by a rectangular voltage, or gate. In figure 100⑤ this gate pulse is shown to be positive during the sweep time

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and is applied to the grid of the cathode-ray tube to reduce the bias sufficiently to make it operative. At the end of the sweep time the grid is returned to a high bias condition and signals returning during the remaining portion of the pulse period cannot appear on the oscilloscope. The same results are obtained by applying a negative gate to the cathode of the indicator tube during the sweep time.

(6) The most commonly used method of estimating range directly on the indicator screen involves the production of range-marker pips in the indicator circuits and superimposing them on the video output of the receiver. The oscillatory circuit which generates the marker signals is gated by a rectangular pulse furnished by the timer, as shown in figure 100⑥. The marker gate enables the marker circuits to operate during the sweep time only and may be either positive or negative, depending on the input requirement of the marker generator.

(7) to provide the required timing pulses the timer must include the following:

(*a*) A circuit capable of establishing the pulse repetition frequency. This may be simply the grid circuit of an r-f blocking oscillator (discussed in sec. III), a rotary spark-gap type of modulator, a sine-wave oscillator, a multivibrator, or a single-swing blocking oscillator.

(*b*) Means of forming the desired signals with the proper time relations. These may include such circuits as limiters, clampers, peakers, amplifiers, controlled multivibrators, and delay networks.

(*c*) Circuits designed to protect one component from the loading effect of another and to deliver pulses to the loads without distortion. Such circuits include the buffer amplifiers and cathode followers.

28. R-F BLOCKING OSCILLATOR.

a. Repetition frequency stability. (1) The self-synchronized radar systems are, as a rule, simpler than those which are externally synchronized. They are suitable for search type radar because their inherent weakness, instability of repetition frequency, is not an important factor. Direct timing of the rest of the system from the transmitter prevents errors in range measurements and prevents the blurring of target signals on the screen.

(2) The blocking action in the grid circuit of the r-f oscillator, of the type shown in figure 38, section III, controls its operation. This blocking action is described in detail in section VII, TM 11-466 and Navships 900,016. The pulse duration is determined by the size of the grid capacitor which charges through the grid-cathode resistance of the tube during the positive swings of the r-f oscillations. After the capacitor has become charged to the voltage at which oscillations

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cease, grid current does not flow and the capacitor discharges through the grid-leak resistor. The value of this resistor establishes the pulse-repetition frequeny.

b. Synchronization for stability. (1) Any small changes in circuit constants or operating conditions affect the stability of the pulse rate. Where its becomes desirable to maintain a pulse-repetition frequency at a value more nearly constant than that which is possible by grid-blocking action alone, a synchronizing signal is applied to the grid of the oscillator. The grid constants are adjusted to produce the approximate repetition rate, and the exact operating frequency is established by the synchronizing voltage.

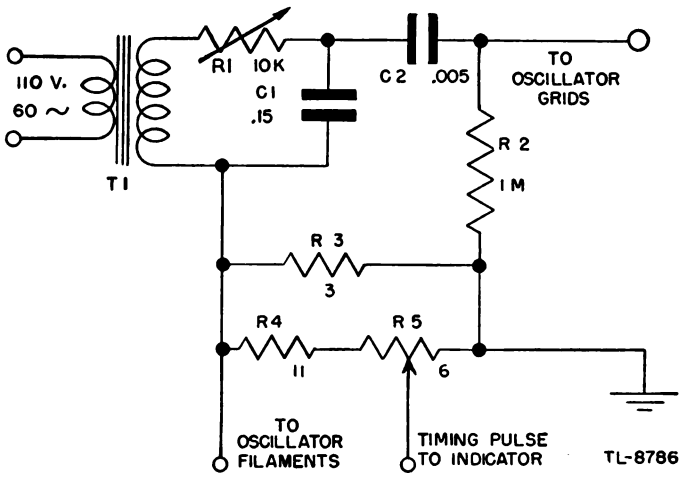

Figure 101. Synchronizing circuit for r-f blocking oscillator.

(2) A typical example of the synchronization of an r-f blocking oscillator is shown in figure 101. The pulse-repetition frequency desired is 60 cycles per second; therefore the grid constants R_2 and C_2 are adjusted to a slightly lower frequency. The 60-cycle synchronizing voltage is supplied by transformer T1. The voltage developed across grid capacitor C2 is shown in figure 102①. The voltage developed across capacitor C1 by the transformer T1 is shown in figure 102②. The minor variation in the synchronizing voltage is due to the charging of capacitor C1 during the transmission time. The effective voltage at the grid is the algebraic sum of these two voltages, as shown in figure 102③.

(3) The capacitor C1 (fig. 101) is placed across the secondary of the synchronizing transformer to provide a low-impedance charging path for grid capacitor C2. R1 provides a means of adjusting the amplitude of the synchronizing voltage. If the voltage is too low, the oscillator will not pulse on the steep slope of the sine wave, so

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that small changes in operating conditions may cause relatively large changes in the repetition frequency. If the synchronizing voltage is too high, the pulse width is reduced because of excessive grid-current flow.

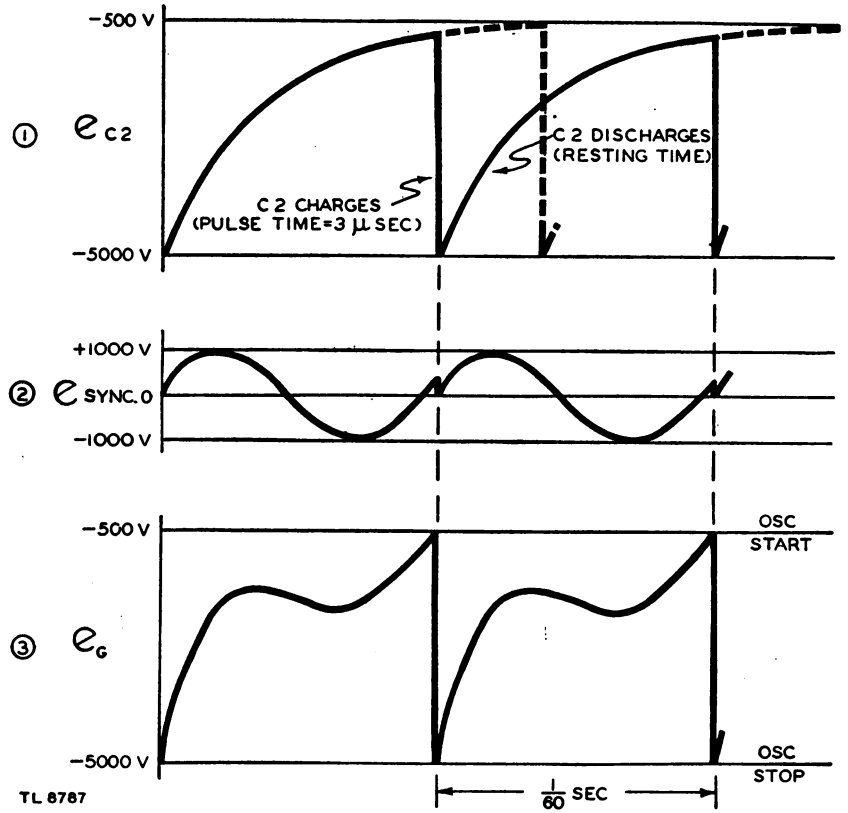

Figure 102. Control of grid of self-pulsed oscillator by synchronizing voltage.

29. ROTARY SPARK GAP.

a. Self-synchronized system. (1) Radar systems utilizing a rotary spark gap modulator may be considered to be of the self-synchronized type, in that the timing function originates within the transmitter circuits. The block diagram of figure 103 illustrates this fact. The analysis of the operation of spark gap modulators is developed in paragraph 35 and only the manner of establishing the timing of the system is to be considered at this point.

(2) In contrast to the systems which are rigidly controlled by a timing oscillator, the rotating gap operates the r-f generator at a comparatively random rate. The approximate timing of the system is set by the rotation of the gap, but the exact timing, over a range of several microseconds, is determined by the random conditions of

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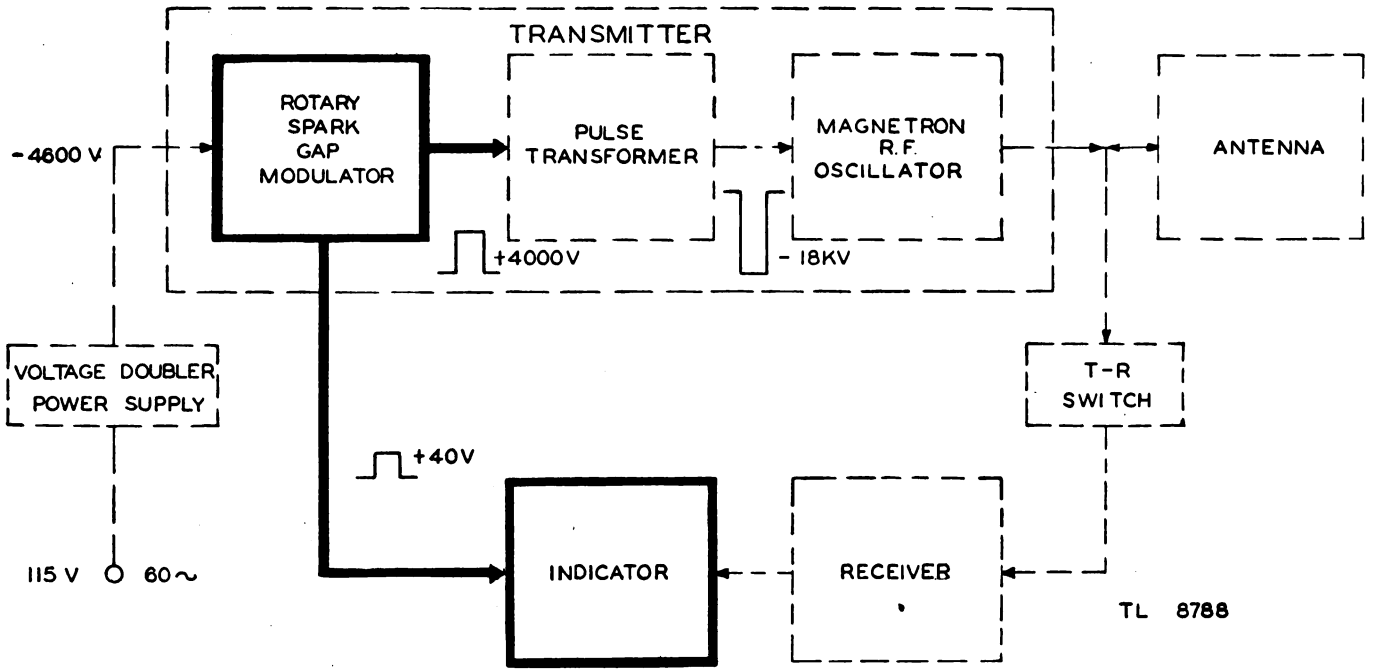

Figure 103. Block diagram of rotary spark gap system showing the timing function.

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the air path between the electrodes. This characteristic is typical of the inherent instability of the self-synchronized systems in general, but these systems have one advantage over rigidly controlled types in that the self-synchronized systems are less susceptible to "jamming" or interference. The transmitted and reflected pulses of all other radar sets move on the indicator screen even if they have the same average repetition frequency.

b. Timing function. (1) The rotary spark gap acts as a switching device in the modulator circuit of the transmitter. The switch consists of a fixed cathode at a highly negative potential and a motor-driven spark wheel with regularly spaced anodes arranged around its periphery and held at ground potential. Assuming a constant speed of rotation, the pulse-repetition frequency of the system is a function of the number of anodes on the spark wheel.

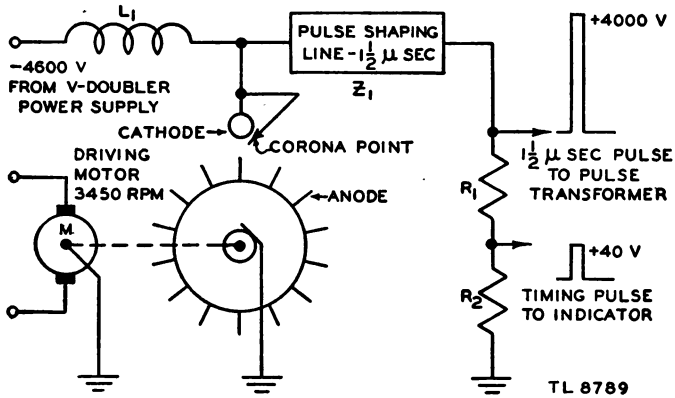

Figure 104. Typical rotary spark gap modulator which provides necessary timing for the system.

(2) In the example illustrated in figure 104, the driving motor has a speed of 3,450 revolutions per minute and the spark wheel has 14 electrodes. Thus a pulse-repetition frequency of approximately 800 cycles per second is produced. The pulse width is determined by the pulse shaping line, Z_1. During the resting time, this pulse shaping line is charged through the resonant charging circuit composed of L_1 and Z_1 to approximately 8,000 volts. As the gap breaks down, the line discharges through its characteristic impedance, producing a +4,000-volt pulse of 1½-microsecond duration. This pulse is applied to a pulse transformer and stepped up to a −18,000-volt level to operate the magnetron. A +40-volt pulse is taken off across R_2 and is used as a timing pulse to synchronize the indicator sweep and gate voltages. This pulse may also be used to trigger such components as range-marker circuits and receiver-gate circuits.

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30. SINE-WAVE OSCILLATOR.

a. As master oscillator. (1) The timing circuits are designed to produce synchronizing signals which are specifically adapted to a given system. Thus it is unlikely that any two radar equipments are able to utilize a common design in their timing circuits. After the specific system requirements for timing functions are established, the proper circuits can be chosen to produce the desired results. The master oscillator employed in the externally synchronized type of radar equipment largely determines the variety of shaping circuits used.

(2) A sine-wave oscillator in which good frequency stability can be maintained is sometimes used as the master oscillator in externally synchronized radar systems. This is especially true of early fire-control equipments in which the range unit uses phase-shifting networks for accurate range measurements. The primary disadvantage of sine-wave timing systems lies in the large number of wave-shaping circuits required, since these contribute prohibitive weight and bulk in some applications.

(3) The sine-wave timer represented here is designed around a 2,000-cycle per second Wien-bridge oscillator and employs circuits which supply timing signals for A-, B-, and C-scan indicators in addition to the transmitter-trigger and receiver-gate voltages. It is designed for use in aircraft with short range AI equipment. The block diagram of the complete timer is shown in figure 105.

b. Circuit analysis. (1) The Wien-bridge oscillator supplies a 2,000-cycle-per-second sine wave through the buffer amplifier to the diode rectifier and to a test jack. The output of the diode is a half sine wave which is applied to the overdriven amplifier. A good square wave of 250-volt amplitude and 250-microsecond duration appears in the plate circuit. This square wave is used to produce the A-scan sweep. It is also applied to a differentiator-amplifier circuit to produce the A- and B-scan indicator gates. The output of the differentiator-amplifier is again differentiated to obtain a short trigger pulse for the B-scan sweep circuits, and for the remainder of the timing circuits. The first of these circuits is that which generates the receiver gate. The trigger pulse is delayed by an artificial line and applied to a multi-vibrator, the output of which is fixed length gate. The time of occurrence of the gate is varied by changing the delay introduced by the artificial line. The second group of circuits which use the output of the differentiator-amplifier, V6, is that which generates the C-scan gate and the B-scan marker pip. The gate is produced directly by the variable multivibrator, and has a trailing edge which can be varied in time. This gate eliminates targets on the pilot's indicator which lie beyond the target in which he is interested.

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So that the operator will know what targets appear on the C-scope, the trailing edge of the C-scan gate is differentiated to obtain a B-scan marker pip. The transmitter trigger is produced by differentiating the trigger pulse from V6.

(2) In figure 106 the usual Wien-bridge circuit employing a 7N7 double triode is shown. C3 is sufficiently large not to affect the phase

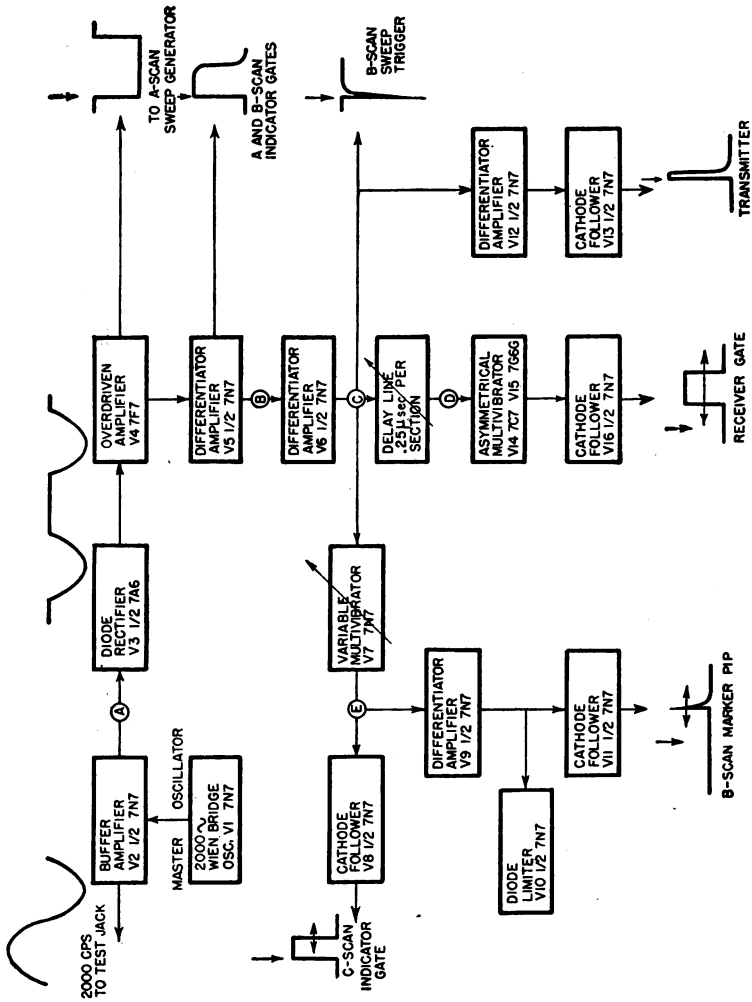
TO A-SCAN SWEEP GENERATOR
A AND B-SCAN INDICATOR GATES
B-SCAN SWEEP TRIGGER
OVERDRIVEN AMPLIFIER V4 7F7
DIFFERENTIATOR AMPLIFIER V5 1/2 7N7
DIFFERENTIATOR AMPLIFIER V6 1/2 7N7
DELAY LINE .25 μsec PER SECTION
ASYMMETRICAL MULTIVIBRATOR V14 7C7 V15 7G66
CATHODE FOLLOWER V16 1/2 7N7
DIFFERENTIATOR AMPLIFIER V12 1/2 7N7
CATHODE FOLLOWER V13 1/2 7N7
TRANSMITTER TRIGGER
TL-8790
RECEIVER GATE
DIODE RECTIFIER V3 1/2 7A6
VARIABLE MULTIVIBRATOR V7 7N7
DIFFERENTIATOR AMPLIFIER V9 1/2 7N7
CATHODE FOLLOWER V11 1/2 7N7
B-SCAN MARKER PIP
BUFFER AMPLIFIER V2 1/2 7N7
OSCILLATOR
2000 WIEN BRIDGE OSC. V1 7N7
MASTER
CATHODE FOLLOWER V8 1/2 7N7
DIODE LIMITER V10 1/2 7N7
2000 CPS TO TEST JACK
C-SCAN INDICATOR GATE

Figure 105. Block diagram of representative sine-wave timer.

of the regenerative voltage passing from the plate of V1.2 to the grid of V1.1. The lamp filament, R4, acting as a variable resistance, controls the degenerative voltage so that the oscillating frequency remains stable at 2,000 cycles per second. The buffer amplifier V2 provides a constant load for the Wien-bridge oscillator.

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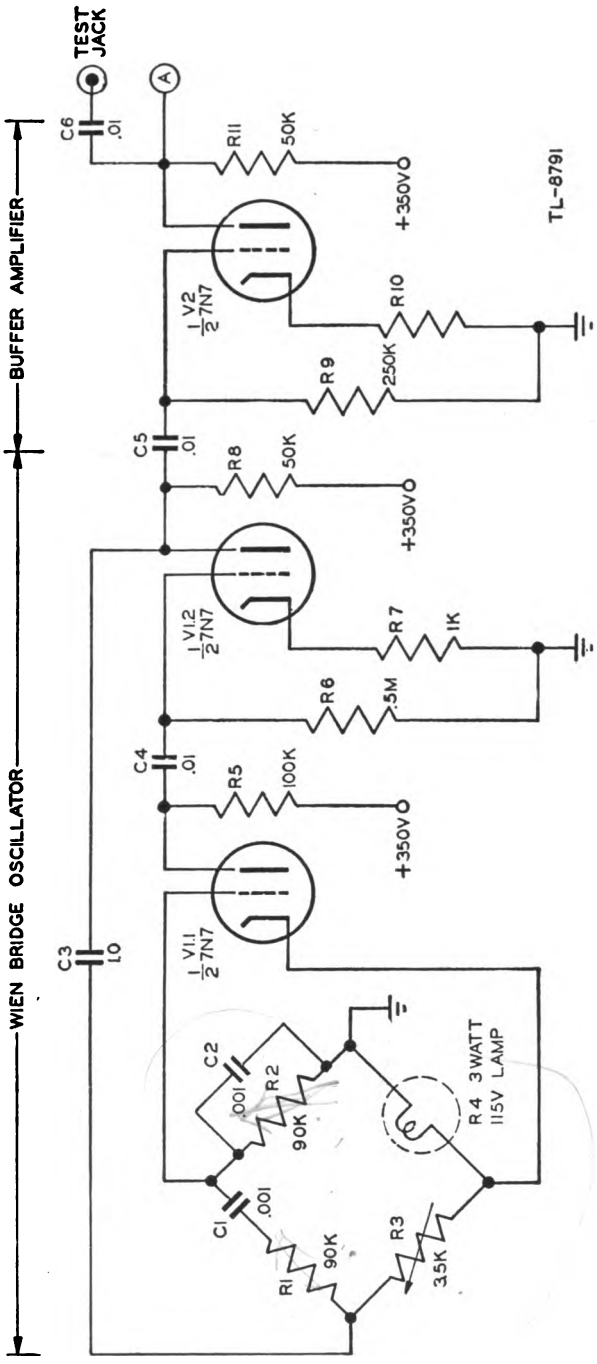

Figure 106. Circuit diagram of timing oscillator and buffer-amplifier section of sinc-wave timer.

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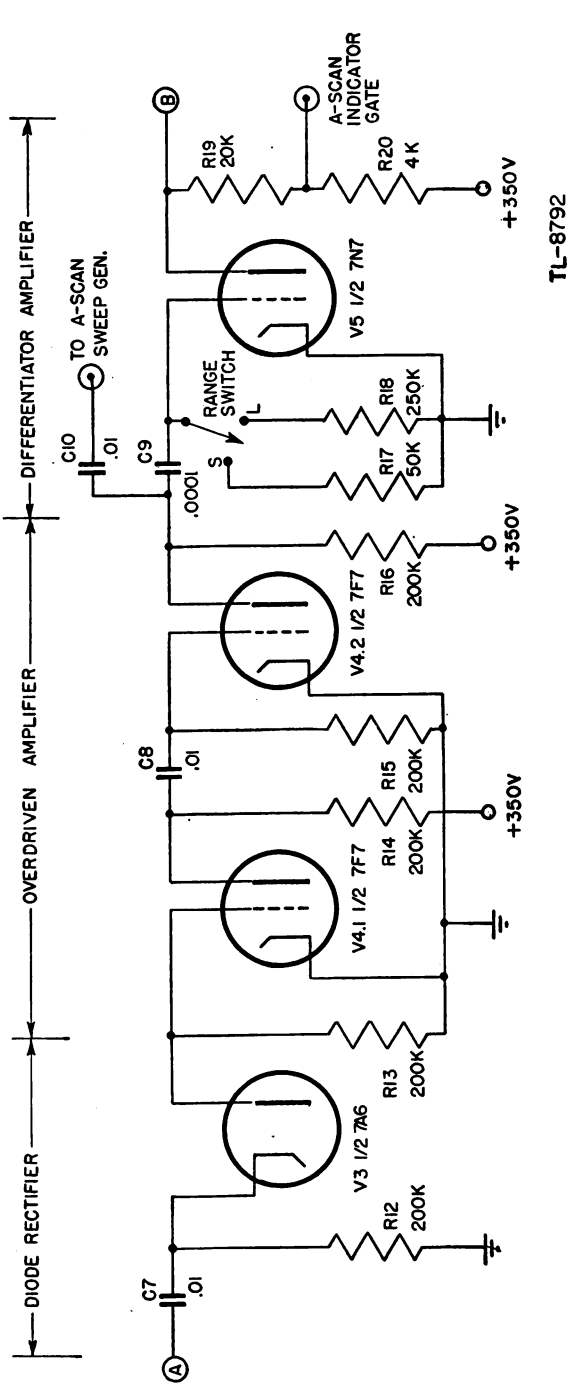

Figure 107. Circuit diagram of A-scan section of sine-wave timer.

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(3) In figure 107 diode rectifier V3 is connected to pass the negative half of the buffer-amplifier output. The negative half-sine wave is applied directly to the grid of V4.1, driving it beyond cut-off. Plate current limiting results are shown in figure 108. The leading edge of the negative-going square wave which appears across the load of V4.2

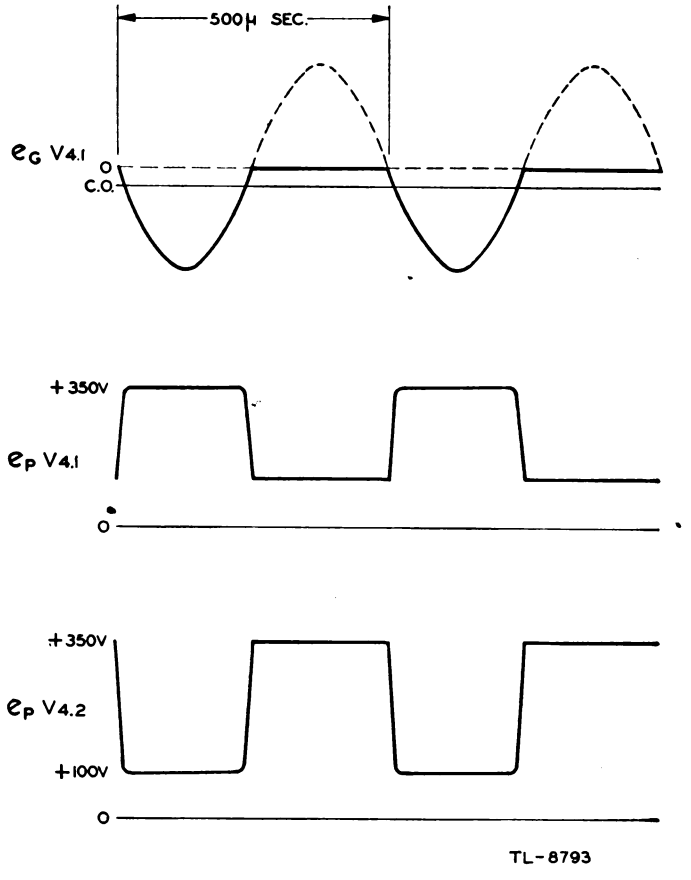

Figure 108. Voltage waveforms in overdriven amplifier.

is used as the zero-time reference for the operation of the various circuits of the timer.

(4) The output of the overdriven amplifier is applied simultaneously to the sweep generator in the A-scan indicator which produces either a 2,000-yard or a 10,000-yard sweep, and to the differentiator input to V5. One section of the range-selector switch places the proper resistor, R17 or R18, in the circuit. The R-C time constant for the short-range position of the switch is 5 microseconds, and for the long-range position is 25 microseconds. The grid of V5 is driven beyond

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cutoff by the negative pulse produced by the differentiator, and is held in this condition for approximately 2.5 R-C seconds. A positive gate pulse appears in the plate circuit which is used to intensify the A- and B-scan indicators (fig. 109).

(5) The gate output of V5 is applied also through the differentiator circuit, C11 and R21, to V6 of figure 110, which is biased close to cut-off by the voltage drop across R22. The output of this amplifier stage, at point *C*, is a very sharp negative-going trigger pulse of approximately

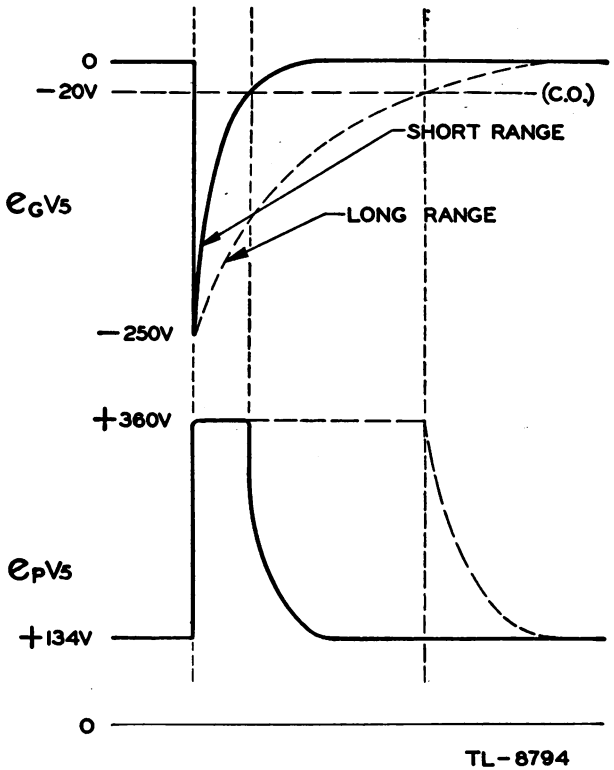

Figure 109. Grid and plate voltage waveforms of V5.

160-volt amplitude. This trigger is used to start the sweep generator in the B-scan indicator. It is applied simultaneously to the delay line in the plate circuit of V6 and to the input circuits of the variable multivibrator V7 and the differentiator amplifier V12.

(6) The C-scan indicator gate voltage is produced by the multivibrator V7 (fig. 111). The operation of the multivibrator is synchronized by the application of the negative pulse, introduced from point C in figure 110 to the grid of V7.2, by way of the voltage-divider network consisting of R24, R28, and R29. V7.2 is cut off by this pulse and remains in a nonconducting state during the time required for

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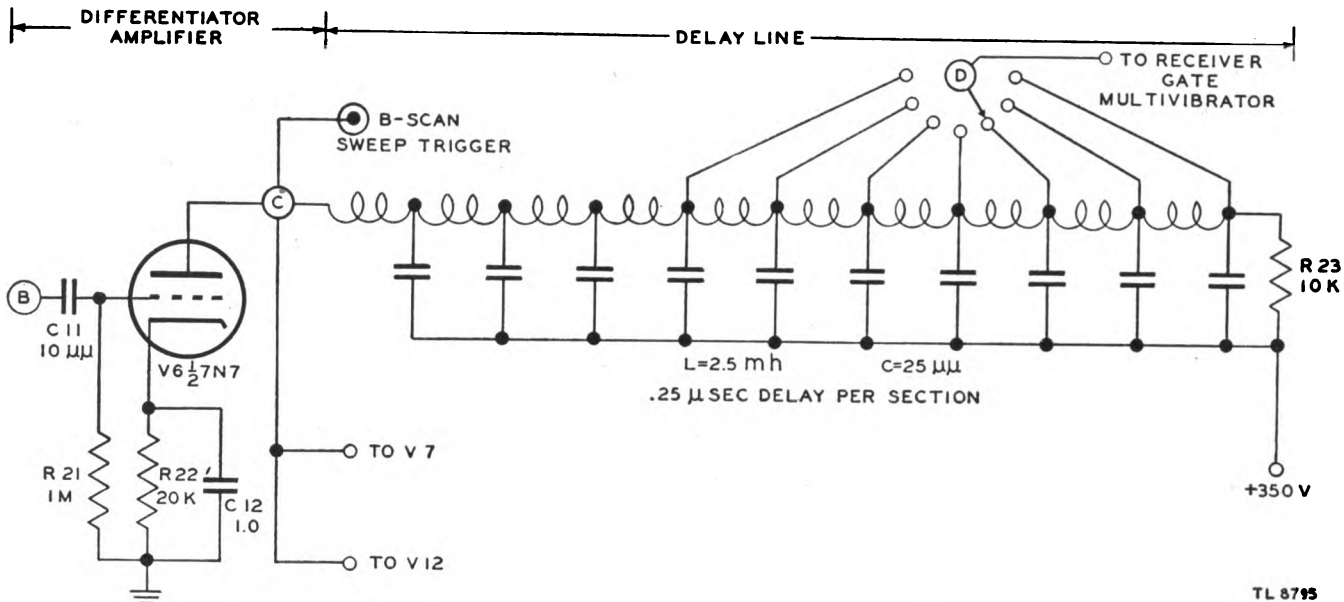

Figure 110. Circuit diagram of B-scan section and delay network of sine-wave timer.

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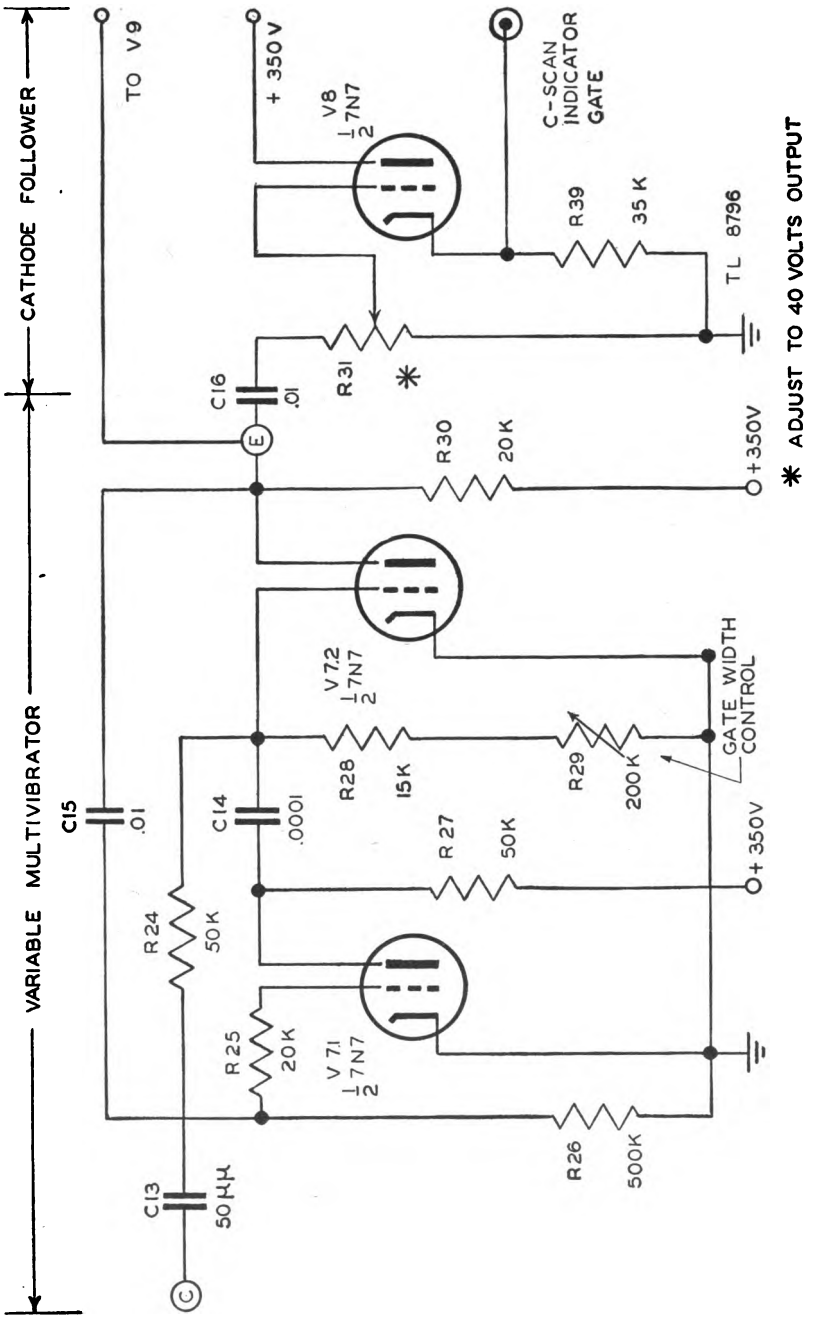

Figure 111. Circuit diagram of C-scan section of sine-wave timer.

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C14 to discharge sufficiently to return its grid above cut-off. The plate waveform of V7.2 during its cut-off time is used as the gate. The discharge rate of C14 is adjusted by the setting of R29, thus determining the width of the gate at point *E*. This variable-width intensifier gate is applied to the C-scope by way of the cathode follower V8. R31 is adjusted to produce a cathode-follower output of approximately 40-volt amplitude.

(7) The gate pulse with a variable trailing edge at point *E* (fig. 111) is applied also to the differentiator input to V9 (fig. 112), which produces a sharp positive peak from the leading edge and a sharp negative peak from the trailing edge. These signals are passed on to the grid of the amplifier V9, which is operating at zero bias. The

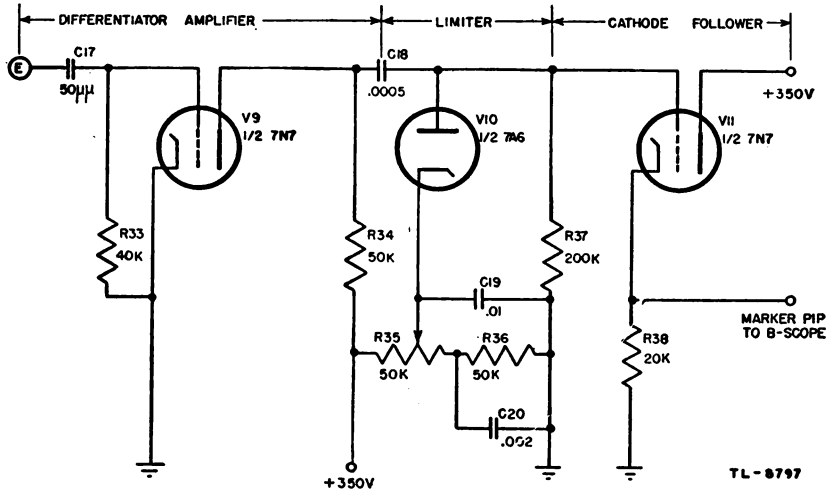

Figure 112. Circuit diagram of marker pip section of sine-wave timer.

trailing peak drives the grid of V9 below cut-off, slightly flattening the positive peak on the plate. The R-C time constant of the grid input circuit of the cathode follower V11 is approximately 100 microseconds, which is long compared to the duration of the pulses applied by the preceding stage, but is short compared to the pulse repetition time as established by the Wien-bridge oscillator. The diode V10 acts as a positive limiter at a potential determined by the setting of the potentiometer R35. The cathode follower passes the positive pulse (fig. 113⑥). This pulse is applied to the grid of the electromagnetic B-scope, producing horizontally across the face of the oscilloscope a bright line, the position of which the operator may control by adjusting R29. As this range pip is produced by the trailing edge of the C-scan indicator gate pulse, it allows the operator to control the range coverage of the pilot's oscilloscope.

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(8) The negative trigger pulse at point *C* of figure 110 is applied to the differentiator-amplifier V12 of figure 114. The input circuit has a time constant of five microseconds which further sharpens the applied pulse. The amplifier is driven to cut-off during the pulse time, producing in the plate circuit a positive pulse with a very steep leading edge. This pulse is coupled to a coaxial cable by cathode fol-

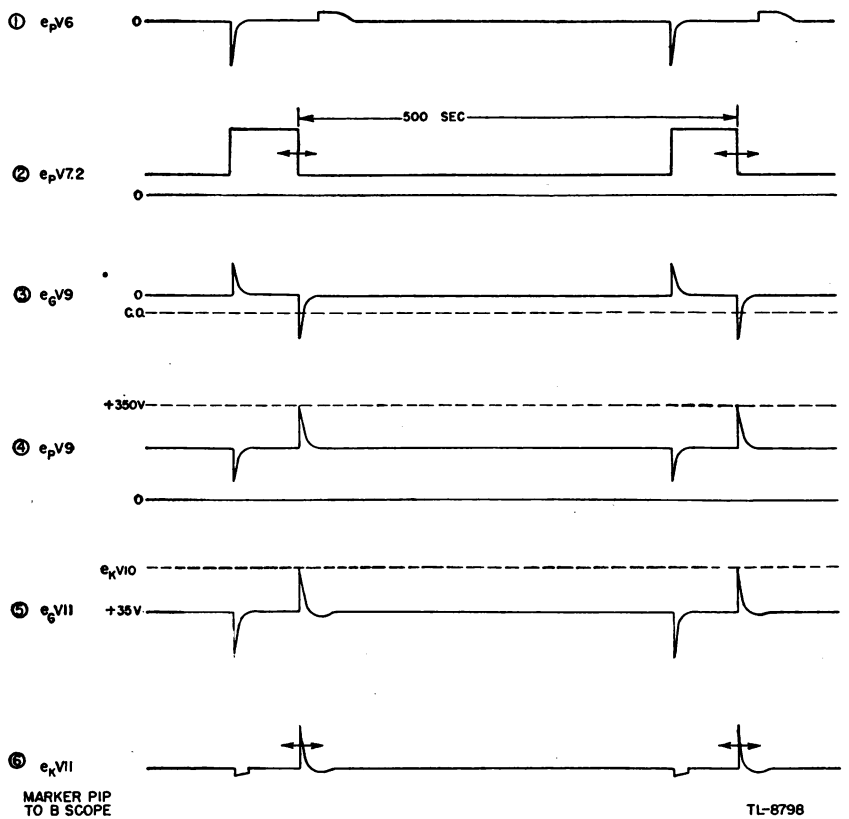

Figure 113. Voltage waveforms of marker pip circuit.

lower V13, and is fed to the transmitter where the steep leading edge serves to trigger the driver circuits into operation.

(9) The negative trigger produced by the differentiator-amplifier V6 (fig. 110) is fed directly to the delay network in the plate circuit, where it is delayed sufficiently to insure its appearance at point D immediately following the end of the transmitter pulse. From point D the delayed negative trigger pulse is fed to the grid of V15 (fig. 115) where it serves to synchronize the operation of the asymmetrical multivibrator composed of V14 and V15. The circuit constants of

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this electron-coupled multivibrator are such that the output taken from the plate of V15 is a positive rectangular pulse with a leading edge determined by the position of the tap D on the delay line and a

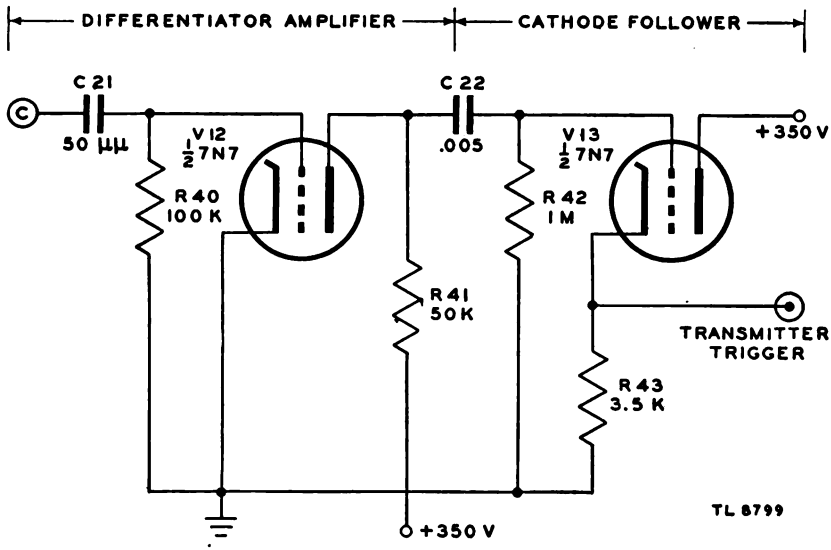

Figure 114. Circuit diagram of transmitter-trigger section of sine-wave timer.

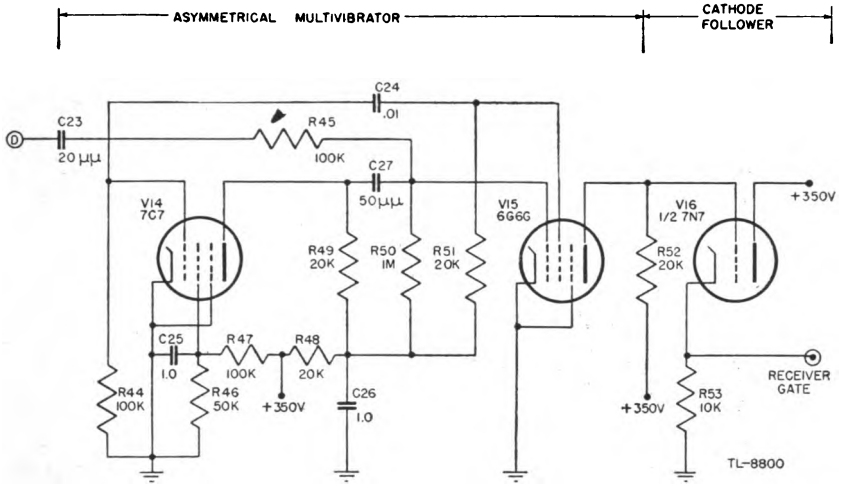

Figure 115. Circuit diagram of receiver-gate section of sine-wave timer.

trailing edge occurring at a fixed later time. This positive gate is coupled by the cathode follower V16 to the early i-f amplifier stages in the receiver to provide screen and plate voltages during the time that it is desired to receive returning echoes.

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31. SINGLE-SWING BLOCKING OSCILLATOR.

a. As master oscillator. (1) The complexity of a timer is dependent on the complexity of the radar system. However, less weight and space are required if the master oscillator is a single-swing blocking oscillator instead of a sine-wave oscillator. The saving re-

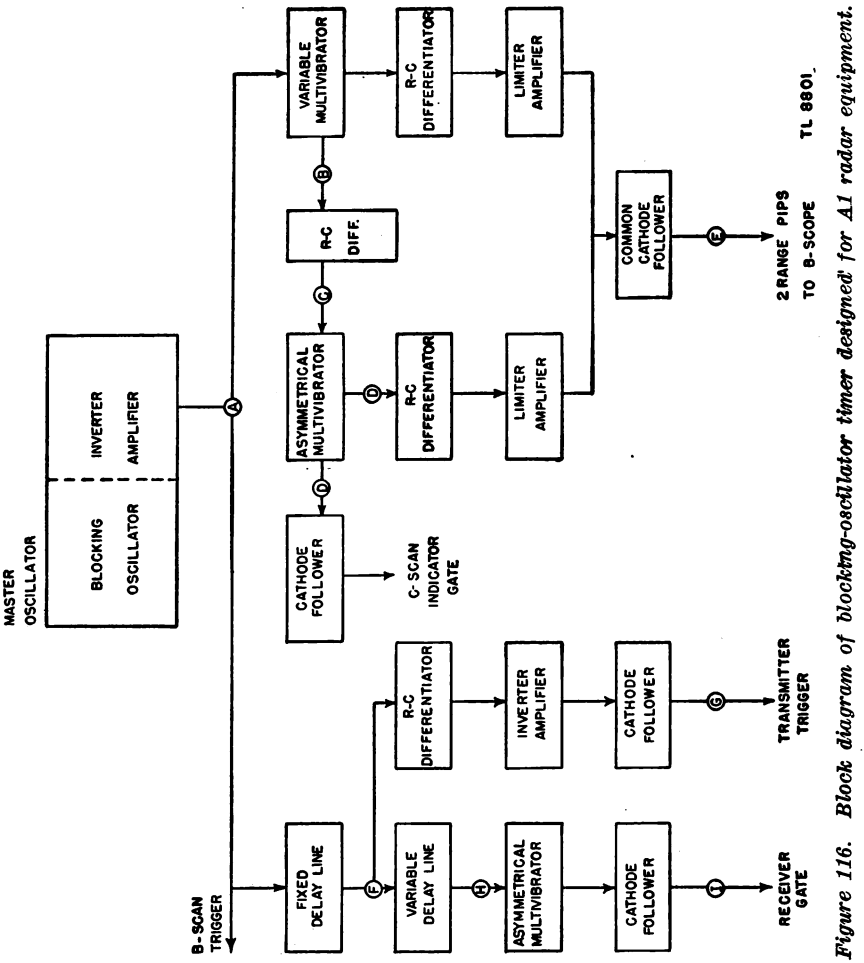

Figure 116. Block diagram of blocking-oscillator timer designed for A1 radar equipment.

sults from the elimination of the wave-shaping circuits that are required to produce a square wave from a sine wave.

(2) The block diagram (fig. 116) represents the use of a blocking oscillator in the timer previously discussed. The similarity is apparent between the timing signals produced here and those produced in figure 105. The waveforms produced in the blocking oscillator timer are shown in figure 117.

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b. Indirect timing. (1) The blocking oscillator is employed as the master oscillator in some recent designs in which critical timing and simplicity are important factors. Simplification of the timer is possible principally because only one type of indicator is used, so that the variety of timing signals is reduced. The block diagram (fig.

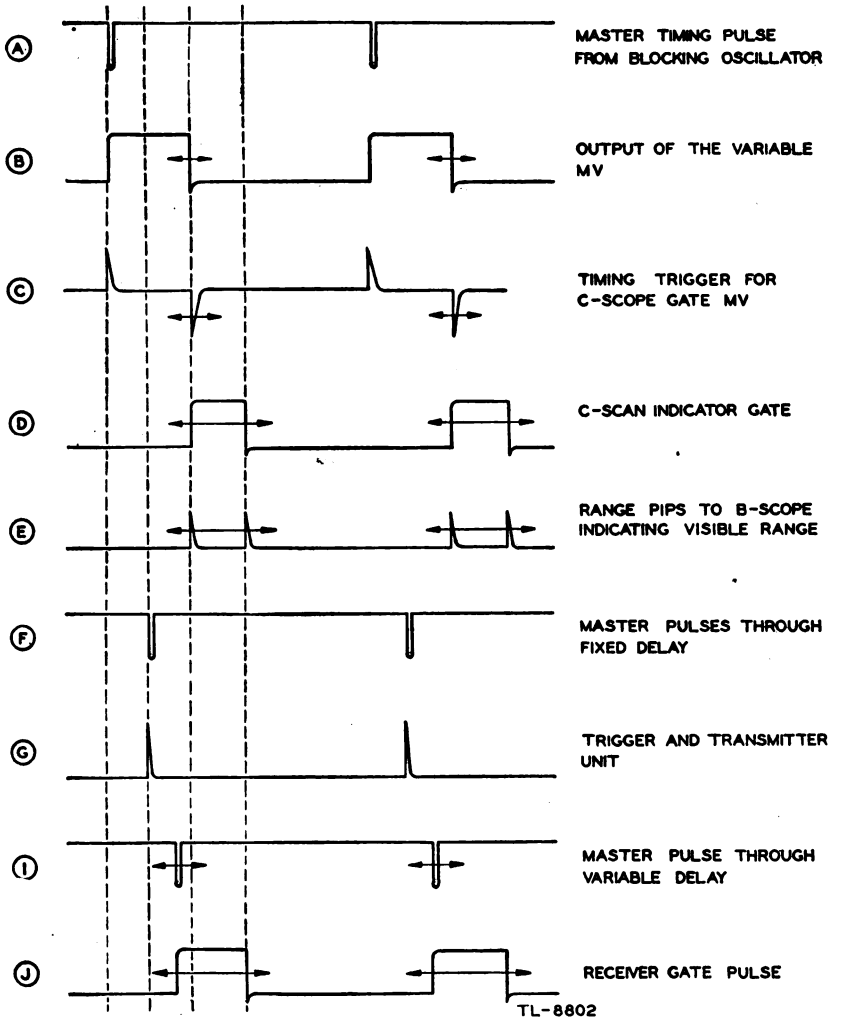

Figure 117. Timing pulses produced by circuits represented in figure 116.

118) illustrates such a timer in which the blocking oscillator establishes the frequency and indirectly controls the required timing signals which synchronize the various components of the equipment. The transmitter is triggered into operation by the master oscillator and a portion of the modulation pulse is coupled to the timing circuits to control their operation.

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(2) The advantages of the repetition frequency stability of the externally synchronized system are realized in this timer. At the same time simplicity is gained by utilizing the modulation pulse as a triggering voltage to operate a multivibrator capable of producing the required timing pulses. The voltage pulses produced within the timer are shown in figure 119 in the proper time relation to the master-oscillator pulse.

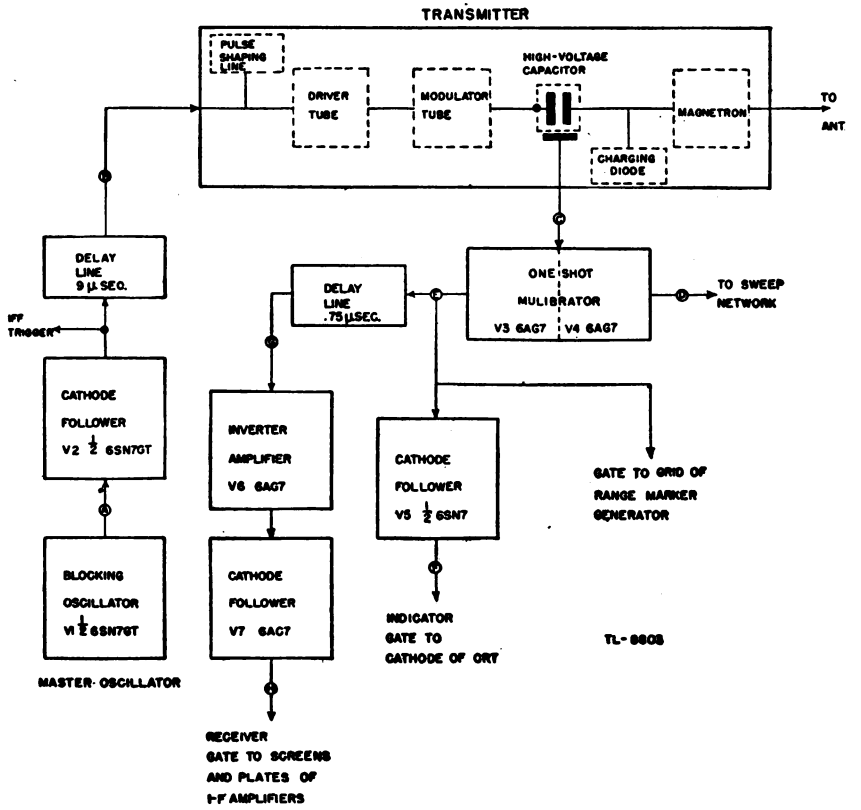

Figure 118. Block diagram of blocking-oscillator timer employing indirect synchronization.

c. Circuit analysis. (1) The output of the blocking oscillator (V1 of fig. 120), developed across secondary S2 of transformer T1 is applied directly to the grid of the biased cathode follower. The operation of the single-swing blocking oscillator is discussed in section VII, TM 11-466, and Navships 900,016. The sharp positive pulse output of the cathode follower is applied directly to the IFF interrogator equipment, but is delayed nine microseconds before triggering the transmitter to compensate for the inherent delays in the IFF

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system and to insure that any returning IFF signal appears on the indicator at the proper range.

(2) The modulation pulse is formed in the driver and amplified in the modulator, after which it is applied to the magnetron. A pick-up plate in the modulator which is capacitively coupled to the

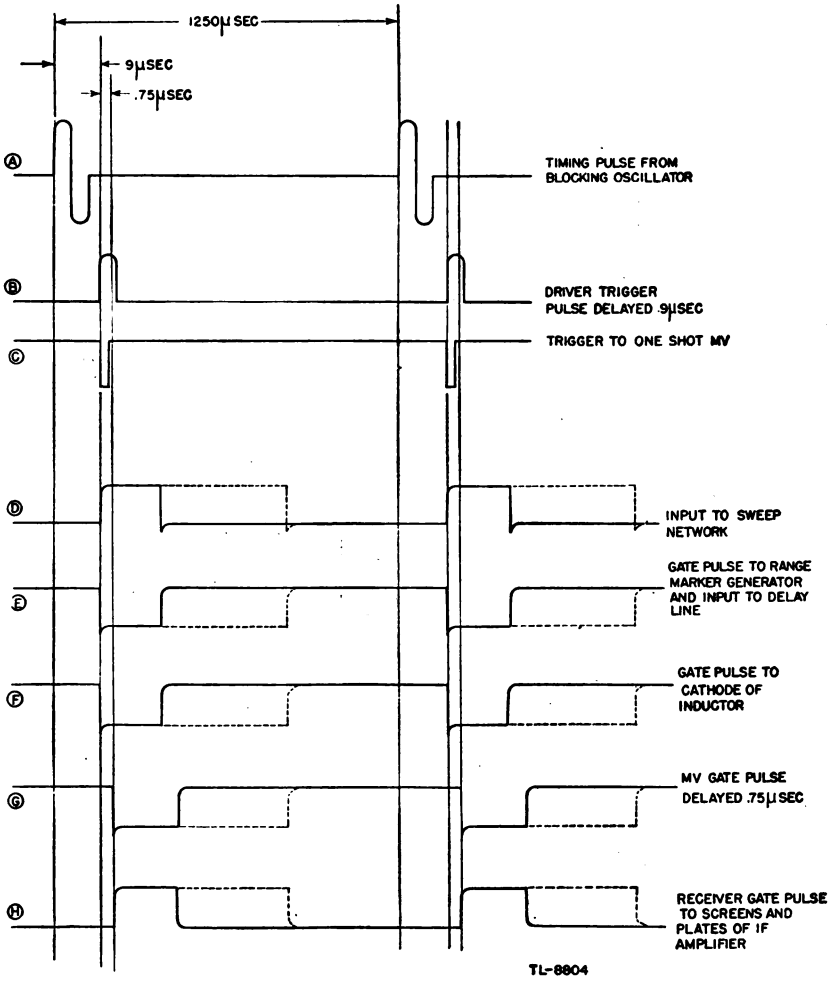

Figure 119. Timing pulses produced by circuits represented in figure 118.

high-voltage capacitor delivers a negative pulse to the grid of V3 (fig. 121) of sufficient amplitude to trigger the electron-coupled multivibrator V3 and V4. The grid of V4 is normally biased beyond cut-off so that V3 is the conducting tube of the one-shot multivibrator. The grid of V3 is returned to +300 volts and the circuit constants are such that the trigger pulse causes V4 to conduct and V3 to re-

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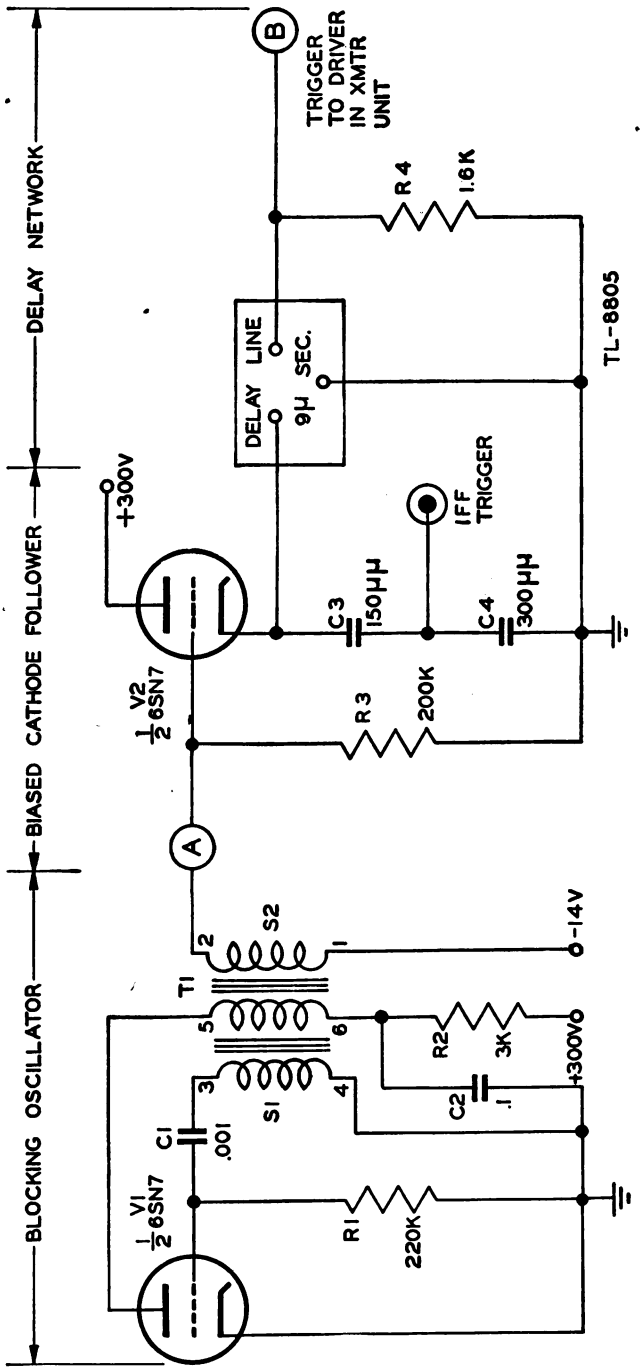

Figure 120. Master oscillator section of blocking-oscillator timer.

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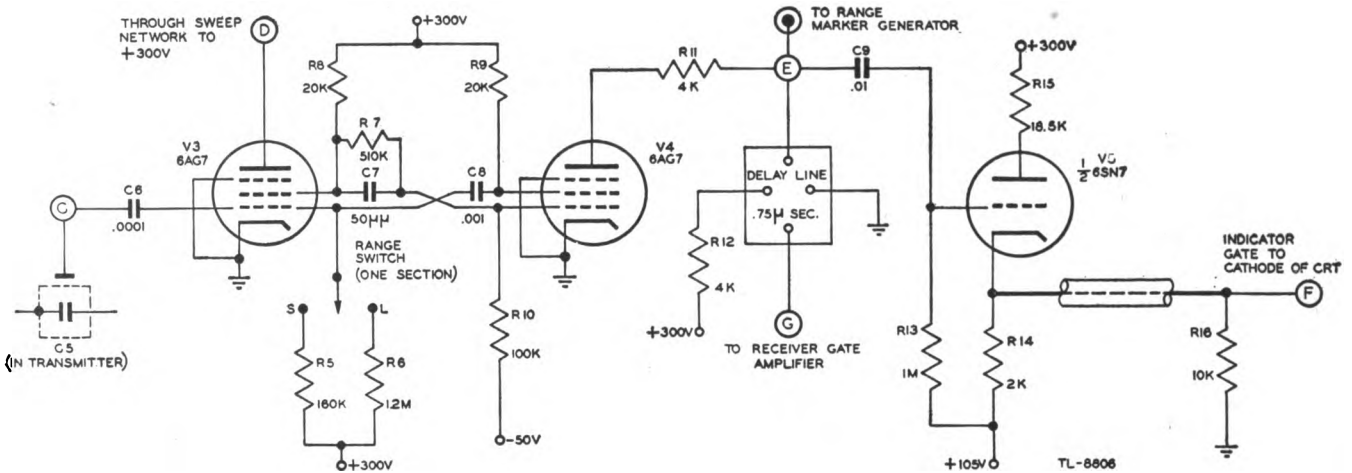

Figure 121. Gate-producing multivibrator section of blocking-oscillator timer.

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main cut-off for the proper time duration as determined by the setting of the range-selector switch. Thus, coincident with the transmitter pulse, the plate of V3 delivers a positive pulse to the sweep-generating network, and the plate of V4 delivers a negative gate of equal width which establishes the operating time of the range-marker generator, the indicator tube, and the receiver.

(3) The negative gate pulse, at point *E* (fig. 121), is applied directly to the range-marker generator in the indicator unit, which is of the shock-excited oscillator type described in section IX. It is applied also through the cathode follower, V5, to the cathode of the

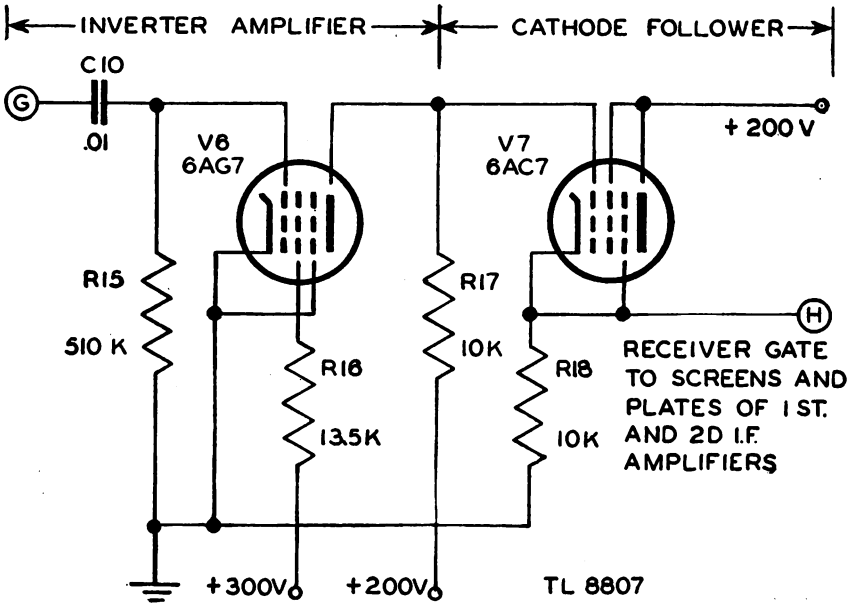

Figure 122. Receiver-gate amplifier section of blocking-oscillator timer.

indicator tube, reducing the bias to a value which will permit the video signals to modulate the intensity of the cathode-ray tube. The cathode follower is cut off as the leading edge of the negative gate pulse is applied to the grid. The voltage on the cathode of the cathode-ray tube drops to approximately +87 volts because of the voltage-divider action of R14 and R16. This reduces the bias on the cathode-ray tube to a value just beyond cut-off and enables any positive video signals to produce fluorescence. As the trailing edge of the negative gate pulse is applied to the grid of V5 it is returned to its normal potential of +105 volts and the cathode rises toward this value, increasing the bias on the cathode-ray tube to a point well beyond cut-off.

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(4) At point *E* (fig. 121) the negative-going gate pulse is fed through another lead to an artificial transmission line which introduces a delay of 0.75 microsecond. This delay enables the receiver to remain inoperative during the transmission time and thus prevents blocking of the video stages as a result of the strong transmittal signal. The delayed gate pulse is then fed to the inverter-amplifier stage (V6 of fig. 122). The screen grid of this tube is returned to a voltage higher than the plate supply which produces a large plate current, holding the grid of the directly coupled cathode follower V7 at a low positive potential. The positive gate pulse developed across the plate load of V6 is coupled to a coaxial cable through V7, and is fed to the receiver-gain control circuits in the receiver chassis where it furnishes the plate and screen voltages for the first and second i-f amplifier stages. As the receiver is unable to amplify and detect any signals received during the time the plate and screen voltages are removed from the i-f amplifiers, its operation is effectively gated in this manner. Video signals are produced and fed to the indicator only during the time of the positive receiver-gate voltage.

32. MULTIVIBRATOR.

a. As master oscillator. (1) A multivibrator is sometimes employed in radar equipment as the master oscillator in the timing system. The major factor which favors the use of this type of timer is the simplicity with which the required timing signals can be produced for the various components. Both positive- and negative-going rectangular pulses of equal but controllable width are produced simultaneously at the two plates of the multivibrator. Thus it is possible to perform the timing functions of the radar system with a minimum of additional timing circuits.

(2) The block diagram of a multivibrator timer is shown in figure 123. The master oscillator consists of a free-running, asymmetrical multivibrator which furnishes directly the following rectangular pulses:

(*a*) *Positive pulses* (*A*, fig. 123).
  1. To the delay tube V2.
  2. To the peaking circuit in the PPI sweep generator.
(*b*) *Negative pulses* (*E*, fig. 123).
  1. To the PPI sweep generator.
  2. To the A-scope sweep generator.
  3. To the sweep clamping circuits for synchronization.
  4. To the paraphase amplifier V6.

(3) The output of the delay tube, Ⓑ, is fed simultaneously to the cathode of the PPI oscilloscope as a gating pulse, Ⓓ, and to a differentiator circuit to produce a trigger for the transmitter, Ⓒ. The nega-

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tive pulse output of the paraphase amplifier is placed on the cathode of the A-scope as a gating pulse, Ⓕ, and the positive pulse output is differentiated to produce a trigger for the IFF equipment, Ⓗ.

b. Circuit analysis. (1) The master oscillator circuit is shown in figure 124. The asymmetrical multivibrator employs a 6SN7

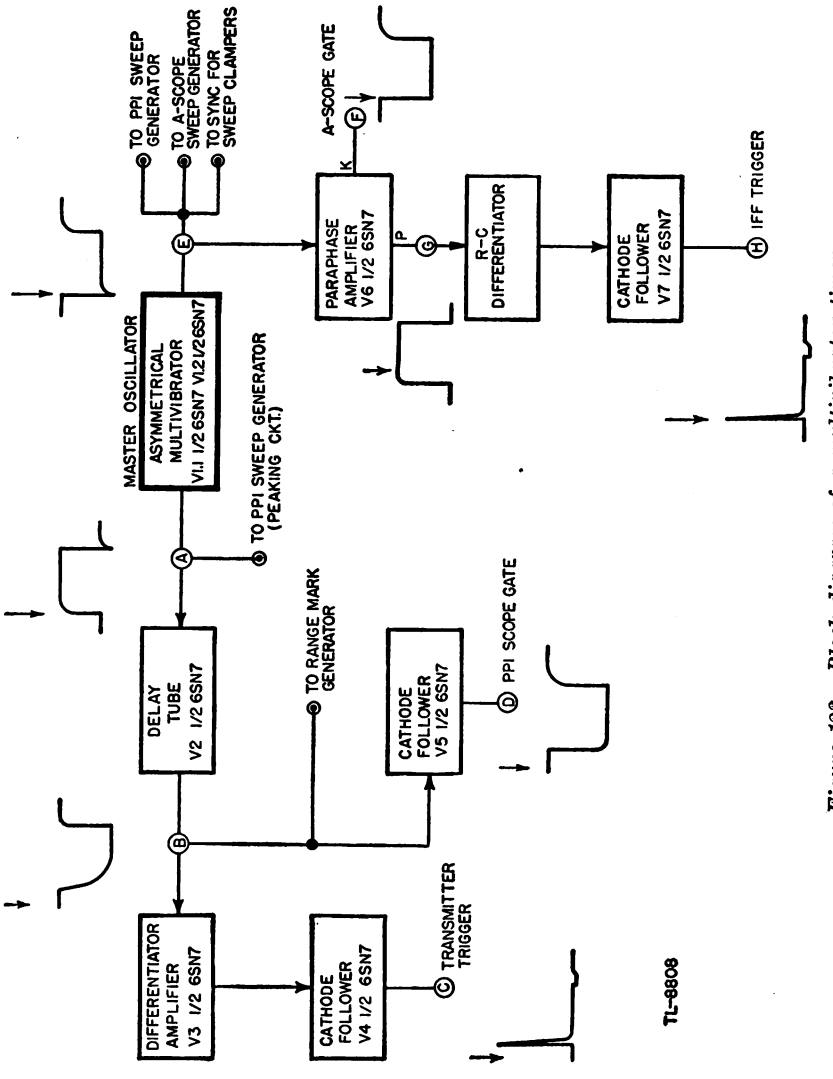

Figure 123. Block diagram of a multivibrator timer.

double triode and the necessary circuit constants to produce an oscillating frequency of approximately 650 cycles per second for radar operation. Provision is made for switching to beacon operation by reducing the oscillating frequency to approximately 325 cycles per second. The multivibrator is free running and is unconventional only

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in the manner of switching to different ranges. By means of balanced grouping of resistors in each grid circuit the range switch controls the time constants in the grid circuits without changing the repetition frequency of the circuit.

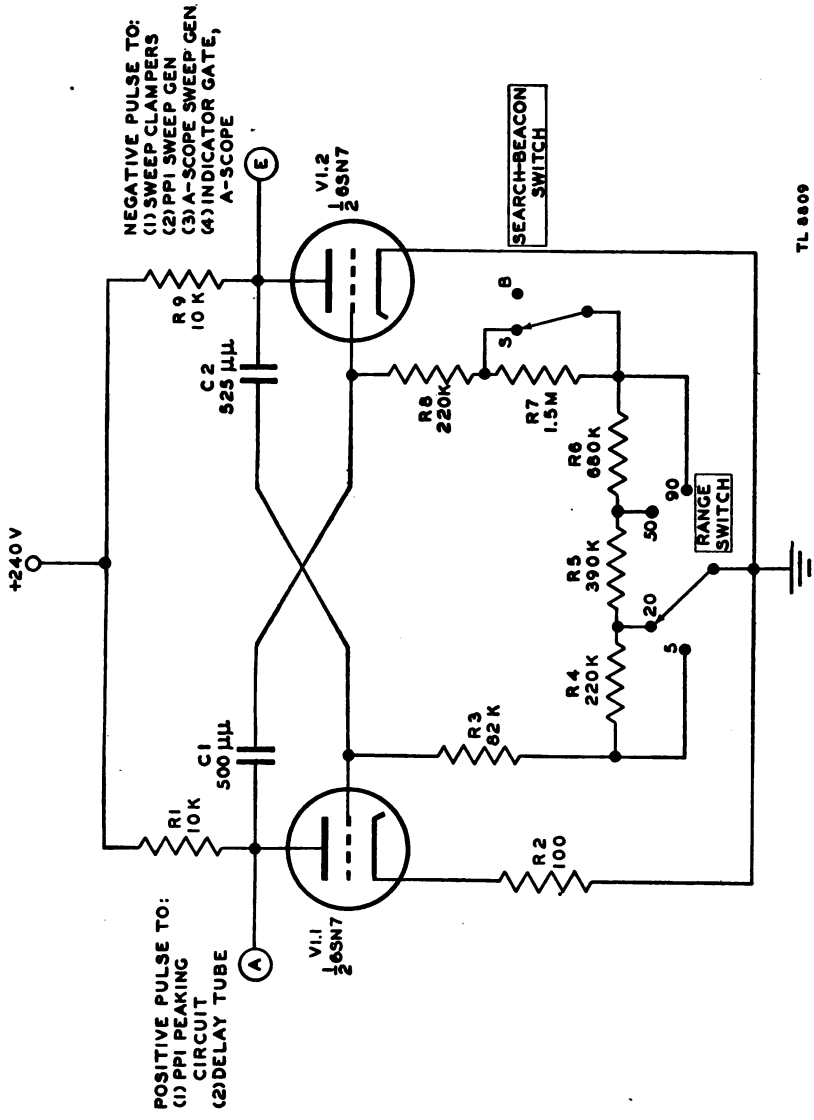

Figure 124. Asymmetrical multivibrator used as master oscillator.

(2) Four ranges, 5, 20, 50, and 90 miles, are available. One section of the range-selector switch establishes the proper ratio of grid resistances to produce pulses at the plates of V1.1 and V1.2 which are slightly wider than the operating range requires. The time during which V1.1 is conducting and V1.2 is cut off is utilized in producing the timing

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signals for the system components. Thus the leading edges of the pulses which occur simultaneously at points *A* and *E* establish the zero-time reference of the system.

(3) The plate and grid waveforms of V1.1 and V1.2 for the four settings of the range switch are shown in figure 125.

(4) The positive gate voltage produced at point *A* is fed to the peaking circuit in the PPI sweep network and to the input of the delay tube

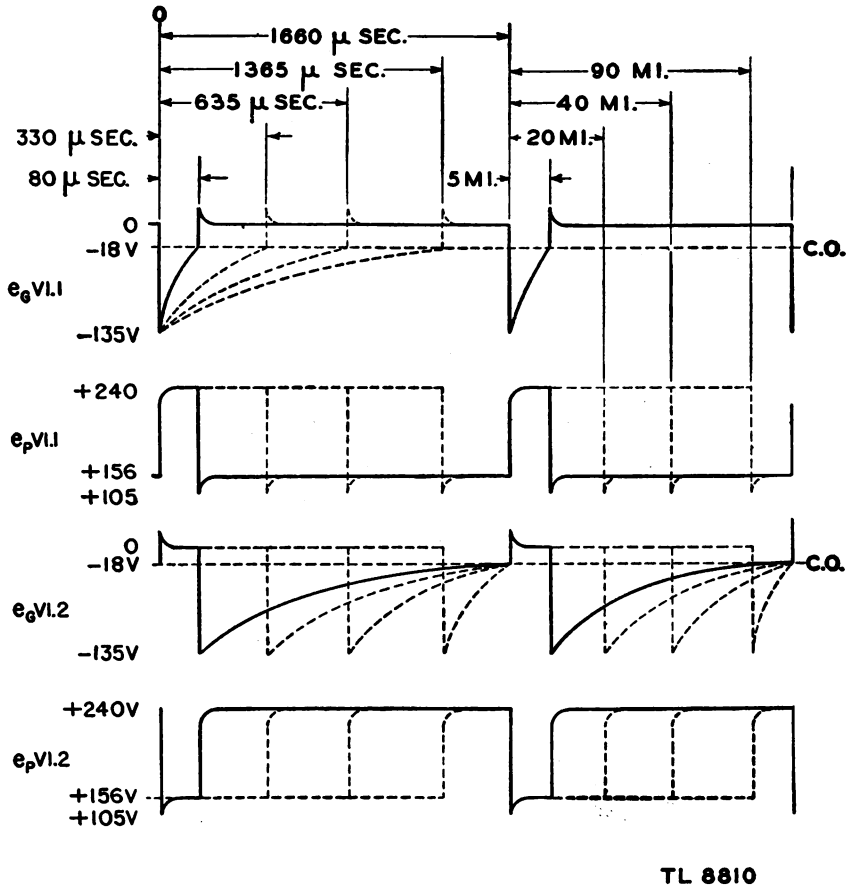

Figure 125. Grid and plate voltage waveforms of V1.1 and V1.2.

V2. The delay circuit is shown in figure 126. The cathode is tied to a positive potential of 105 volts and the grid is directly connected to the plate of V1.1. During the time V1.1 is conducting, the voltage at the grid is not sufficient to hold the grid above cut-off. A delay of approximately 10 microseconds is produced by using an integrator input circuit consisting of R10 and C3. As V1.1 is cut off, the rise in plate voltage is applied across R10 and C3. The capacitor charges

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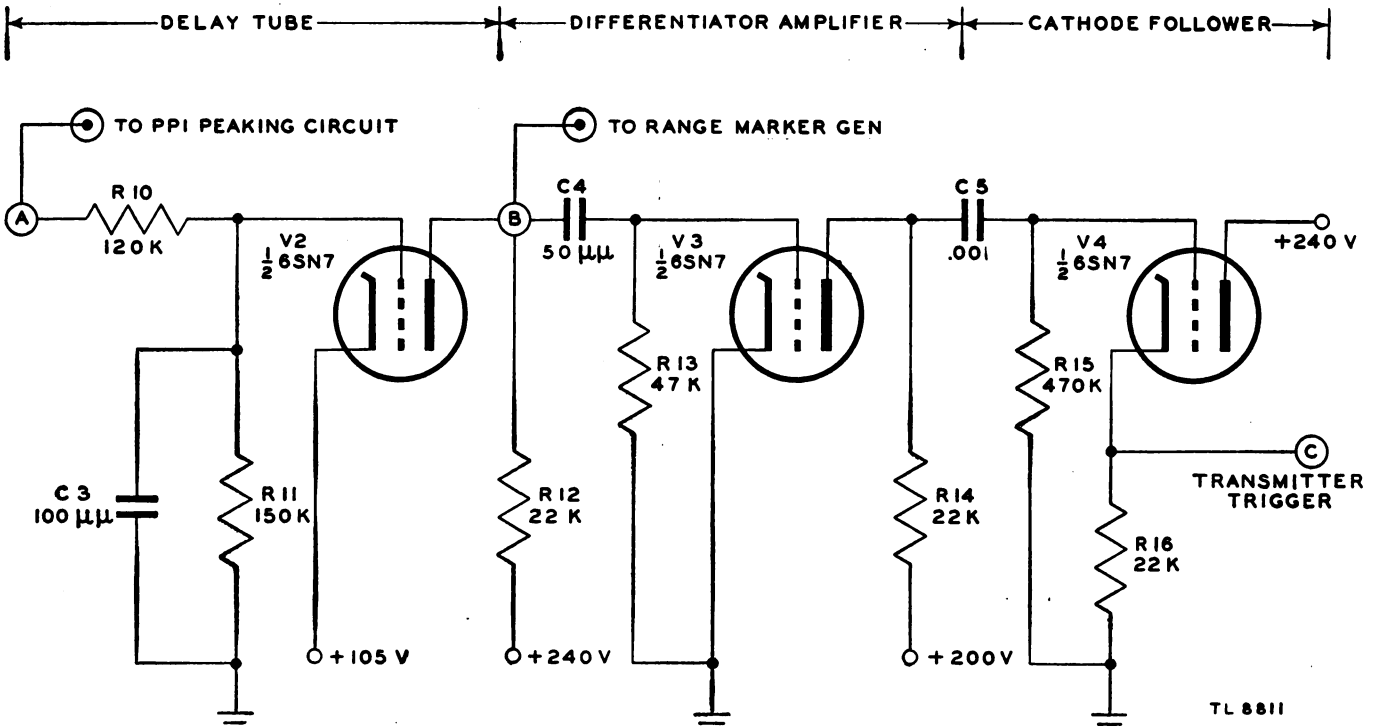

Figure 126. Circuit diagram of transmitter trigger section of multivibrator timer.

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at a rate determined by the R-C time constant of the charging path. Thus the grid of V2 can reach cut-off only after a time delay determined by the rate at which C3 charges. Figure 127 illustrates the delay action occurring in the input circuit of V2.

(5) The delayed negative-going pulse output of V2 (Ⓑ, fig. 126) is delivered to the range-marker generator for the purpose of starting and controlling the duration of its operation. It is applied simultaneously to amplifier V3 through the differentiator circuit consisting

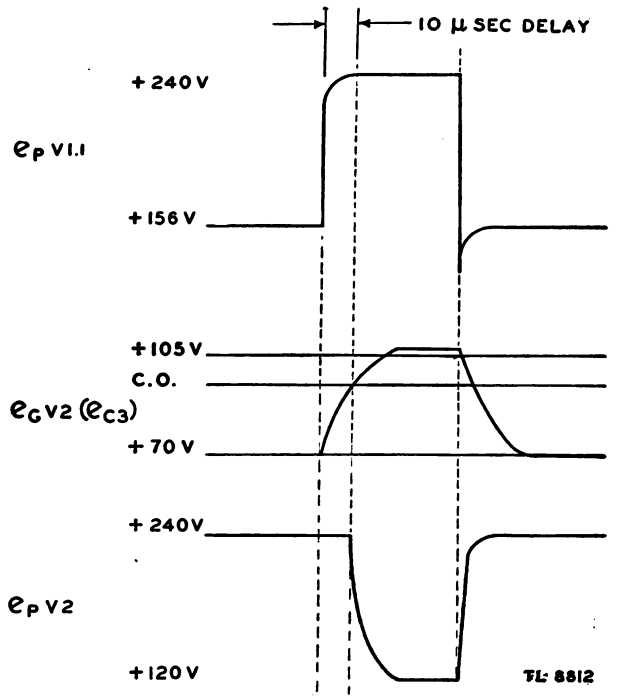

Figure 127. Grid and plate voltage waveforms of delay tube V2.

of R13 and C4. The differentiated leading edge drives the grid of V3 beyond cut-off, stopping the flow of plate current. The differentiated trailing edge is limited to a low-amplitude value by the flow of grid current. The output of the amplifier is essentially a positive pulse with a steep leading edge and a flat top of four or five microseconds. This positive pulse is coupled to a coaxial cable by the cathode follower V4 and is delivered to the transmitter as a driver trigger. The grid-input to V3 and cathode-follower output waveforms are shown in figure 128.

(6) The negative pulse occurring at point *B* (fig. 126) is fed also to the zero-biased cathode follower V5 (fig. 129), which couples it without inversion to the cathode of the PPI oscilloscope. There are ap-

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proximately 20 volts across R18 with no signal on the grid of the cathode follower. This places the cathode of the PPI tube at +20 volts. The grid potential may be adjusted to a potential sufficiently negative to hold the tube well beyond cut-off. As the negative pulse from the delay tube is applied to the grid of V5, the cathode of the oscilloscope tube drops to zero voltage, thus reducing the negative grid bias on the cathode-ray tube sufficiently to permit any positive video signals on the grid to produce fluorescence. The i_p vs. e_g char-

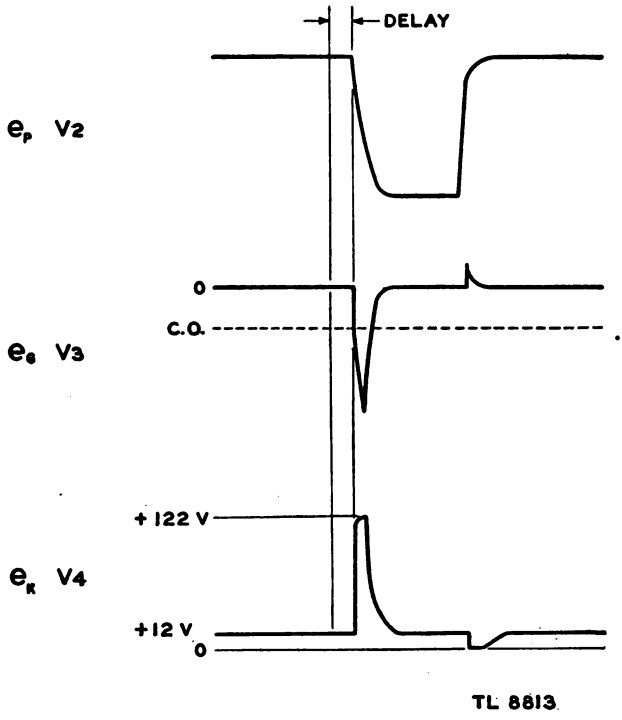

Figure 128. Transmitter trigger waveforms.

acteristic of the cathode-ray tube is employed in figure 130 to illustrate the grid- and cathode-voltage relationships.

(7) The plate of V1.2 produces a negative-going pulse (Ⓔ, fig. 124), coincident with the positive pulse produced at point Ⓐ. This pulse times the operation of both A-scope and PPI sweep generators and provides a synchronizing voltage for the PPI sweep-clamping circuits. It also is fed to the paraphase amplifier shown in figure 131. The voltage across cathode resistor R20 is approximately 30 volts with no signal on the grid. The negative pulse on the grid drives the tube to cut-off, causing a 30-volt pulse to be developed across R20. This negative pulse is applied to the cathode of the A-scope to

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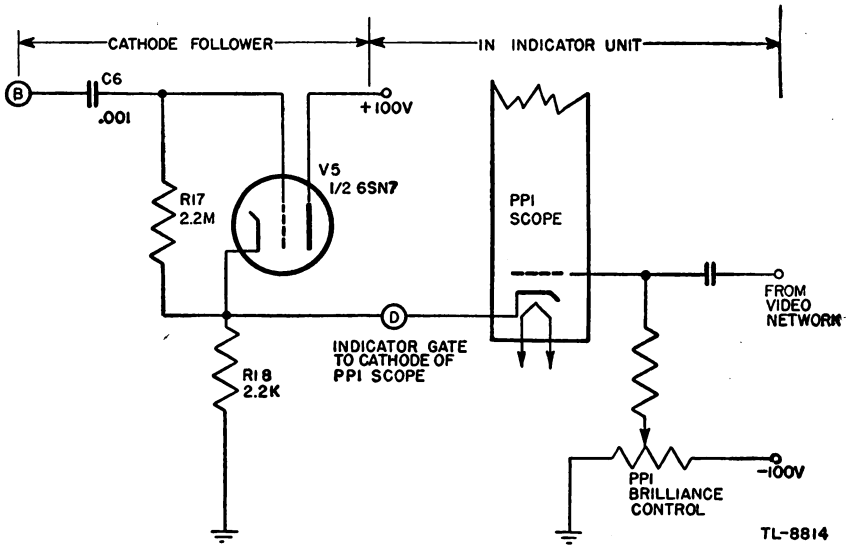

Figure 129. Circuit diagram of PPI gate section of multivibrator timer.

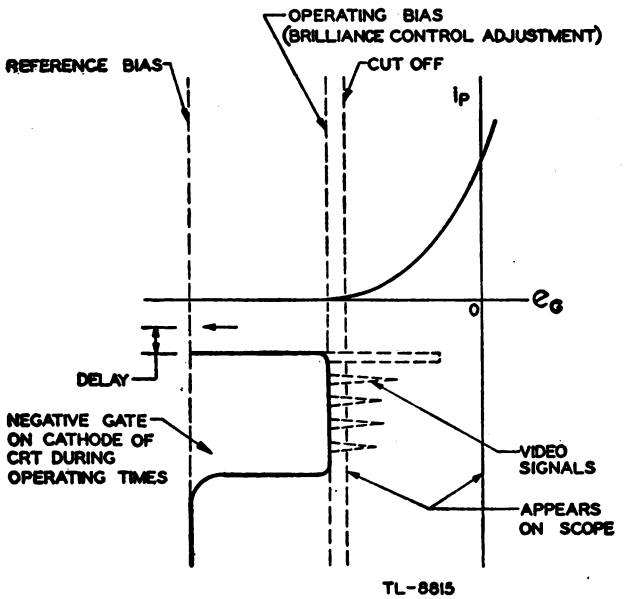

Figure 130. The i_p vs. e_g characteristics illustrating means of controlling bias of indicator.

remove the bias voltage and to intensify the tube for the duration of the sweep.

(8) A positive rectangular pulse is produced across the plate load R21 of V6 simultaneously with the pulse across R20. This pulse is

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applied through the differentiator, consisting of R22 and C8, to the grid of cathode follower V7. The differentiated leading edge of the input pulse is used to trigger the interrogator equipment of the IFF system. The amplitude of the positive trigger at point H with the coaxial cable connected is approximately 15 volts.

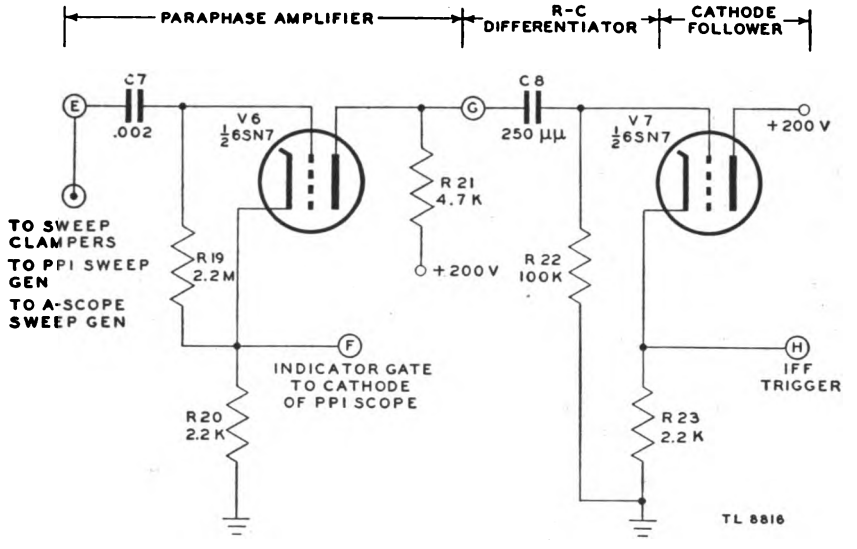

Figure 131. Circuit diagram of A-scope gate and IFF trigger section of multivibrator timer.

(9) The multivibrator timer provides the means of starting the indicator-sweep voltages ahead of the transmitter pulse. This, however, does not affect the over-all range accuracy, since the PPI indicator gate circuit and the range-marker generator are operated by the same delayed pulse that produces the transmitter trigger.

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Section VI
Transmitters

33. GENERAL.

a. Selection of r-f generator. (1) The selection of the r-f generator is governed chiefly by the carrier frequency at which the system is to operate. The carrier frequency depends on several factors, among which are the desired directivity of the antenna, the effect of frequency on propagation, and the tactical application of the system.

(2) After determining the carrier frequency, the next step is to select the r-f generator. The triode oscillator is able to produce high peak power in pulse operation up to 400 megacycles per second. Because of interelectrode capacitances, electron transit time, lead inductances, and stray capacitances, the triode is incapable of producing a pulse of large peak power at higher frequencies. However, triode oscillators may be used to produce pulses of relatively low peak power at frequencies up to 600 megacycles per second. Such an r-f generator is useful in lightweight sets where high-power output is not essential. Above 600 megacycles, the magnetron is by far the most efficient r-f generator known at present, and is used almost exclusively in microwave radar. In a few cases a special form of triode, called the lighthouse triode, is used in low-power transportable microwave radar sets.

b. Selection of method of pulsing. (1) Three important pulsing methods are in use at present: self-pulsing in a triode blocking oscillator; production of a low-power pulse which is shaped and amplified to the proper magnitude to operate the r-f generator; and the production of a high-power pulse which is applied directly to the r-f generator. The method used depends on the type of r-f generator, the accuracy of range measurement to be obtained, and the minimum range desired.

(2) The triode oscillator is pulsed equally well by all three of the above methods. The method which is used with a magnetron, however, must produce a rectangular pulse with very steep sides in order to apply a fairly constant voltage to the magnetron during the pulse time. Otherwise power is wasted by the production of oscillations of

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several different frequencies. Early pulsing systems for magnetrons were of the type that produced a low-power pulse and amplified it to the proper magnitude.

(3) The limitation on the use of such pulse-amplifier systems is the amount of pulse power which can be produced without the use of many tubes in complicated circuits. This upper limit is about 300 kilowatts. The high-power pulse-generating systems use spark gaps capable of controlling enormous peak powers. Radar sets are now available which by using rotary gaps to extend the life of the system, produce r-f pulses of peak power exceeding a megawatt.

(4) If extreme precision of range measurement is necessary, the leading edge of the transmitted pulse must be as steep as possible in order that the zero time for each sweep may be accurately determined. In applications where very short ranges must be measured—for example, in aircraft interception—the transmitted pulse must be short and the trailing edge of the pulse must be very steep. This is necessary so that the change-over from the transmitting condition to the receiving condition may be made as rapidly as possible to avoid masking of nearby targets. The self-pulsing triode oscillator does not meet either of these requirements well enough to permit its use in precise range-measuring systems. However, because of its simplicity, this type of pulsing is of considerable value in search systems where a high degree of accuracy and measurement of very short ranges are not required.

34. R-F GENERATORS.

a. Triode oscillators. (1) Although triode tubes may be operated with their control grids positive to produce very high frequency oscillations, as in the Barkhausen-Kurz oscillator, such circuits are not used in radar transmitters because they are too inefficient to supply the high peak power necessary. The triode oscillators which are used are of the negative-grid type, connected in a two-tube, push-pull circuit.

(2) The tuned circuits used in triode radar transmitter circuits are usually short-circuited quarter-wave sections of two-wire transmission line. These tuned circuits may be connected in the oscillator circuit in any of the ways shown in figure 132. Oscillations are produced by feedback through interelectrode capacitances. Other connections may be used, particularly when the length of the filament leads within the tube is such that special precautions must be taken to eliminate degeneration in the cathode circuit and the feedback of r-f energy into the power line.

(3) All the oscillators as being shown are self-pulsed. In ② the grid is connected to B+ through a high resistance in order to establish

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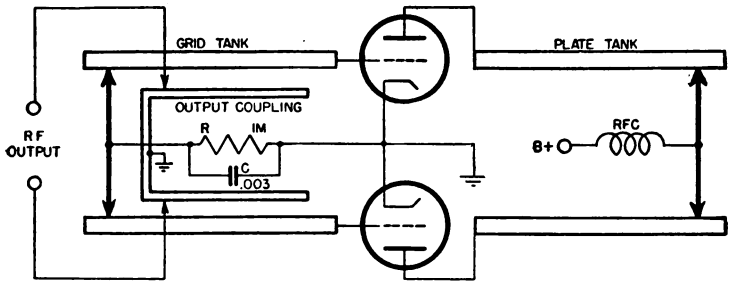
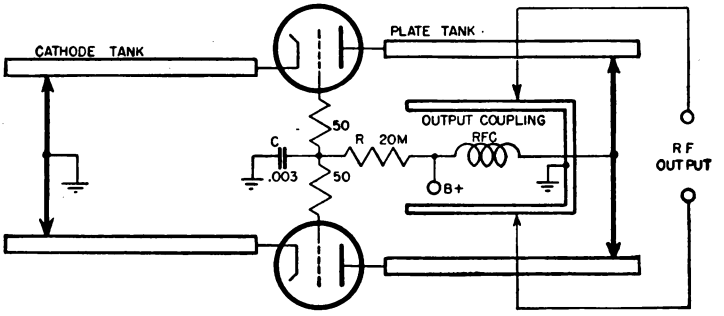
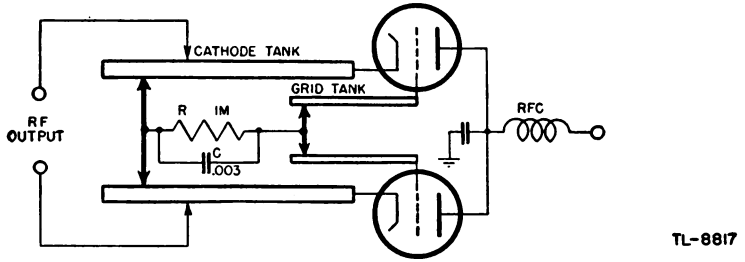
a slightly more stable pulse-repetition frequency than is possible with the connections shown in ① or ③. In all cases the flow of grid current charges capacitor C to produce a bias large enough to stop oscillation. A reduction in the size of the grid-leak resistor or an increase in the size of the capacitor will prevent self-blocking; all types may then be pulsed by common forms of modulators.



① TUNED-GRID TUNED-PLATE OSCILLATOR; LOAD INDUCTIVELY COUPLED TO GRID.



② TUNED-PLATE TUNED-CATHODE OSCILLATOR; LOAD INDUCTIVELY COUPLED TO PLATE.



③ TUNED-GRID TUNED-CATHODE OSCILLATOR; LOAD COUPLED DIRECTLY TO CATHODE.

Figure 132. Representative circuits of push-pull oscillators.

(4) Energy may be coupled out of the oscillator inductively, capacitively, or by direct connection. Capacitive coupling is seldom used alone, but it may be used in conjunction with inductive coupling. Inductive coupling to the grid circuit is used in some radar transmitters, but usually this type of coupling reduces the Q of the grid tank circuit so much that it cannot be used to control the frequency

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of the oscillator effectively. One important difficulty that arises from inductive coupling to the plate tank circuit (fig. 132②) is that the voltage between the coupling line and the plate tank circuit is the sum of the d-c voltage and the r-f voltage. Because of this large voltage, the coupling line cannot be moved too close to the plate tank because of the possibility of an arc-over. The degree of coupling is so limited in some cases that optimum coupling cannot be obtained. This difficulty is overcome in the direct coupling arrangement shown in ③. There is no d-c voltage on the cathode; therefore, the transmission line may be coupled to the cathode tank to any desired degree by adjusting the position of the output tap.

b. Ring oscillator. (1) The power output of a two-tube push-pull oscillator is limited by the peak plate current that can flow in the tubes and the power dissipation of the plate. To increase the power output it is necessary to increase the current-carrying capacity of the tubes, or to increase the number of tubes in the circuit. Because of electron transit time, interelectrode capacitance, and lead inductance, it is undesirable to increase the physical size of the tube to provide greater current-carrying capacity. Although increasing the temperature of the filament will permit greater emission, this change greatly shortens the life of the tube. Increasing the number of tubes by paralleling allows a higher peak power to be generated, but it also increases the effect of the interelectrode capacitances. When it is necessary to build an oscillator of high power, tubes are added in pairs in series to form a *ring* circuit (fig. 133).

(2) The ring oscillator shown is an extension of the oscillator of figure 132①. The effect of the interelectrode capacitances in this type of circuit is half of that for the same tubes connected in a push-pull parallel circuit. Addition of tubes in series to form a ring therefore permits a given type of tube to be used at a higher frequency or allows the use of tubes which are physically large.

(3) The ring oscillator functions because of the feedback of energy from plate to grid through interelectrode capacitance and because of the voltage distribution on the plate and grid lines. As discussed in TM 11-466 and Navships 900,016, proper adjustment of the tank circuits causes a regenerative voltage to be fed back through the grid-plate capacitance. At the same time standing waves of voltage are established on the sections of transmission lines which cause the voltage at one end of the line to be out of phase with the voltage at the other end. Assume that the grid signal of V1 (fig. 133) is positive at a given instant. The plate signal of V1 will be at a minimum, or negative maximum. The plate of V2, approximately a half-wavelength away, is positive because of the standing wave of voltage on the tuned transmission line. The signal on the grid of V2 is pro-

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duced by interelectrode capacitance as a negative maximum, in order to reinforce the plate current. Continuing around the ring in this manner, the grid of V4 is at a negative maximum to close properly with the grid V1, a half-wavelength away. Plate relations are maintained by always adding tubes in pairs, if a larger number is needed.

(4) The physical construction of the ring oscillator normally is arranged to have the tubes placed in an approximate circle with the tank circuits on the inside of the circle. This arrangement permits

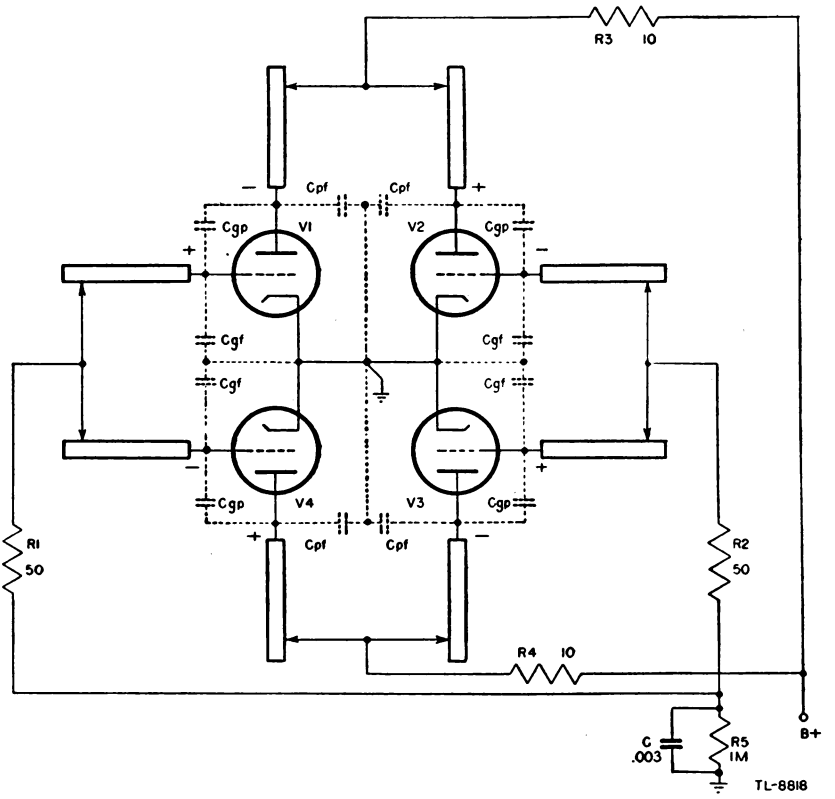

Figure 133. Diagram of tuned-grid tuned-plate ring oscillator.

symmetrical connections between circuit elements, and allows the output coupling to the transmission line to be of relatively simple construction. Figure 134 shows one method for obtaining energy from the tank circuits. The plate lines are supported vertically between the tubes, with the shorting bars at the lower ends. The polarity of voltage at the plates is as indicated and this causes the currents in the shorting bars to have the relative direction of flow shown by the arrows. A transmission line with a loop in the end is lowered between the plate lines so as to place the loop near the shorting bars, to provide inductive

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coupling. The magnetic fields produced by the currents in the shorting bars reinforce each other in inducing the r-f voltage in the loop. The line and loop can be made resonant by using a shorting bar a half-wavelength from the loop to insure maximum transfer of energy. The feed line is tapped across the the resonant section in this case.

(5) Any of the push-pull oscillators shown in figure 1 may be connected in a ring circuit to produce a high-peak power output. Since the ring connection reduces the effect of the interelectrode capacitance, tubes of fairly large physical size may be used to produce high-peak output power at frequencies up to 400 megacycles. In order to produce

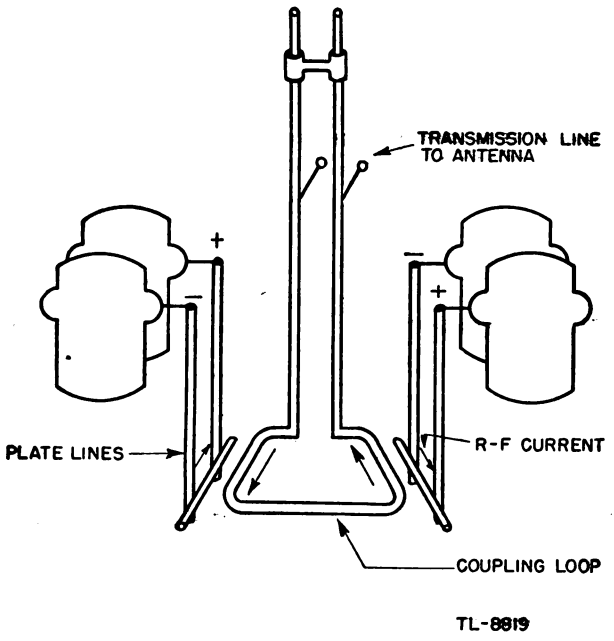

Figure 134. Coupling in a ring oscillator.

even greater peak output power than is possible with the four-tube ring oscillator, additional tubes may be added *in pairs* to the circuit.

(6) The ring oscillator has the disadvantage of having many tuning adjustments in its circuit. If the several adjustments are not made properly, inefficiency will result. Because the ring circuit permits mechanical symmetry in construction, the tuning adjustments may be ganged to a few controls, and the oscillator is relatively simple to operate.

c. Magnetron. (1) The magnetron is used as an r-f generator at frequencies above 600 megacycles per second. Since statement of the frequency in this range may involve rather large numbers, magnetrons are usually described in terms of the wavelength of the r-f energy

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they produce. The general range of wavelengths in which magnetrons are practical is called the microwave region. For use in this region magnetrons have been manufactured which are capable of producing peak output power as high as a megawatt. The efficiency of the magnetron as a device for converting d-c energy to radio frequency energy is approximately 30 to 50 percent.

(2) Magnetrons for radar use require high plate voltages to cause oscillation. During the oscillating period, the current drawn is 10 amperes or more. The effective impedance of the magnetron while it is oscillating is approximately 1,000 ohms. Although it is desirable to reduce the magnetron impedance to a low value to eliminate the necessity for extremely high plate voltage, it has been impossible to reduce the effective plate impedance below approximately 500 ohms, even by special design.

(3) It is characteristic of the magnetron that, if the plate voltage falls very greatly during the pulse, modes of oscillation other than the one desired may result. Oscillation in this manner causes serious loss of power, lowered magnetron efficiency, and difficulties in tuning the system, since unwanted frequency components are produced in the output. Therefore, the voltage applied to the magnetron must rise to the full value as soon as possible and remain constant during the pulse, and decrease to zero in a short time at the end of the pulse. Hence the magnetron requires a fairly rectangular modulating pulse.

35. DRIVER MODULATOR SYSTEMS.

a. General. (1) The triode type of r-f generator may be either self-pulsed or externally pulsed, while the magnetron is always externally pulsed. The general requirements of the modulating or pulsing system are about the same for both types. When the pulse is formed in low-power circuits and then amplified to produce the actual transmitter pulse, a driver is commonly employed to shape the pulse and a modulator is employed to produce the required amplification and apply it to the r-f generator.

(2) If the shape of the modulating pulse need not be controlled accurately, the trigger pulse from the timer may be amplified in a power amplifier, as illustrated by the system of section IV. This is the simplest form of driver modulator. When the pulse shape and duration must be accurately controlled, as in radar sets of short range, more elaborate circuits are used. Such applications generally require a driver in which the pulse is formed by an artificial transmission line, and then applied to a modulator. The occurrence of the pulse is controlled by the output of the timer.

b. Bootstrap drivers. (1) The bootstrap driver uses the trigger pulse from the timer to start the discharge of an artificial line

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through a gas tube. The pulse formed is amplified by a bootstrap amplifier from which the driver takes its name, and is applied to a conventional modulator.

(2) A simplified circuit for producing a rectangular pulse by the use of an artificial transmission line is shown in figure 135. The characteristic impedance of the transmission line is 2,500 ohms. The resistor, R2, across which the output pulse is to be developed is equal to this characteristic impedance. Resistor R1, through which the line is charged, is made very much larger than the characteristic impedance so that it is an apparent open circuit during the discharge of the line. The capacitors are all charged to 600 volts if switch S is left open for a sufficient time. If the switch is closed after the line has been charged, a current immediately starts to flow through R2. The line may be considered as a battery with an internal impedance of 2,500 ohms during the discharge time (fig. 136). The voltage across R2 is

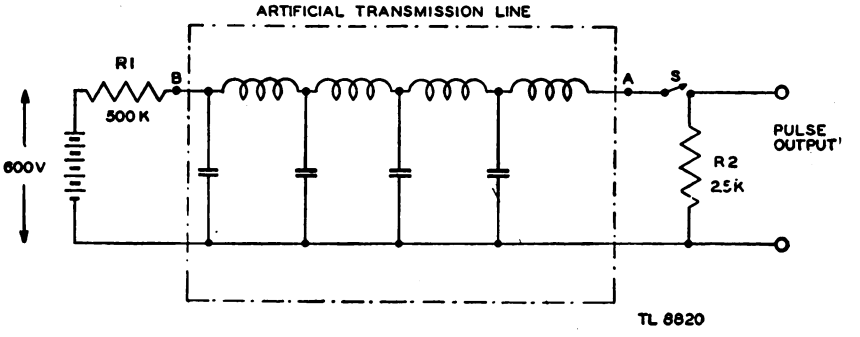

Figure 135. Simple circuit for producing a pulse from an artificial transmission line.

one-half the voltage to which the line was charged, or 300 volts, since half the available voltage is lost across the 2,500-ohm internal impedance, Z_0. If the network consisted only of capacitors, the discharge would follow an exponential curve, and the voltage across R2 would not be constant. However, the inductance and capacitance of the line are so designated that the discharge rate is practically constant.

(3) The discharge of the artificial line can be explained best as follows: At the instant that the switch (fig. 135) is closed, the voltage at point A falls to 300 volts. This can be looked upon as a traveling wave of -300 volts applied at point A to reduce the voltage there immediately from 600 to 300 volts. As the wave moves from A to B the voltage across the line is reduced from 600 to 300 volts. On reaching point B, the wave sees an open circuit, since resistor R1 is very large. The wave is reflected without change in sign, and immediately reduces the voltage at point B from 300 volts to zero as the wave travels back

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to point *A;* and the remaining 300 volts across the line is canceled out. On reaching point *A*, the wave has reduced the voltage across all sections to zero, the wave itself disappearing because it is absorbed by a load which matches the characteristic impedance of the line. The pulse formed across R2 by the line discharged lasts for the time required for the traveling wave to move from the switch end of the line to the open end and back.

(4) The complete circuit diagram of the transmitter with a bootstrap driver is shown in figure 137. A thyratron, V2, is used instead of the mechanical switch shown in figure 135, to discharge the artificial transmission line. The line is connected between the −500-volt and −1,100-volt taps on the power supply, so that it is charged to a voltage of 600 volts through resistor R5.

(5) A positive-going timing pulse with a steep leading edge is applied to the driver through coupling capacitor C1 and isolating diode

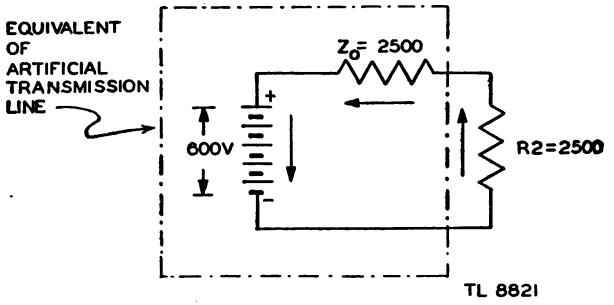

Figure 136. Equivalent circuit of artificial transmission line during discharge.

V1. The positive trigger pulse causes the thyratron V2 to ionize. The current which flows through V2 must come from the discharge of the artificial line because R5 is too large to allow the flow of current sufficient to maintain ionization. The discharge of the artificial line through V2 and R6 produces a −300-volt pulse across R6 during the discharge.

(6) Tube V3 is a double beam-power tube but for convenience it is shown in figure 137 as a single tube. The tube normally is cut off, since its cathode is connected to the −1,100-volt tap and its grid is connected to the −1,250-volt tap on the power supply. The net bias on the tube is therefore −150 volts, which is ample to prevent conduction. When the artificial line discharges, the −300-volt pulse developed across R6 is coupled to the grid of V3 through C10, causing the tube to conduct strongly. The cathode of V3 rises from 1,100 volts below ground to a positive potential with respect to ground because of the voltage drop across R9.

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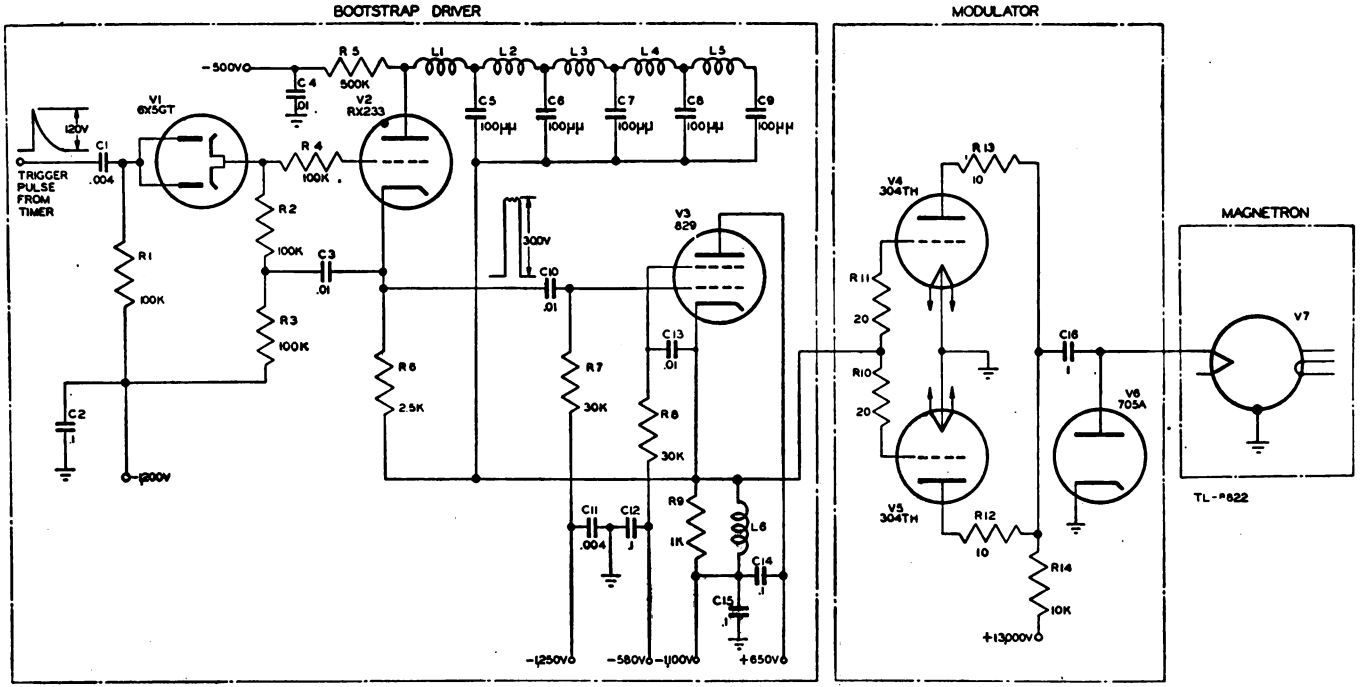

Figure 137. Schematic circuit diagram of transmitter with bootstrap driver.

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(7) The life of thyratron V2 is shortened by positive ion bombardment of the cathode if the grid is driven sufficiently negative to cause acceleration of the ions toward the cathode. This condition is avoided by using diode V1 and capacitor C3. The trigger pulse is coupled to the grid of V2 through capacitor C1 and diode V1. The positive swing of the pulse causes diode V1 to conduct and produce a signal voltage across R2 and R3. The drop across R2 is applied directly between grid and cathode of V2 through C3. When the pulse is removed capacitor C1 discharges, but, since the diode cannot conduct, the negative voltage resulting does not appear at the grid of V2. The pulse developed in the cathode of V2 is coupled back into the grid through C3, causing the grid to rise with the cathode, and thus prevents a negative voltage on the grid from this source. Resistor R4 is used to limit grid current through V2. Since gain is essential in the operation of this driver, a bootstrap amplifier is used. The bootstrap circuit includes elements which cause the voltage on the grid of the amplifier tube to rise with the cathode voltage, maintaining a constant signal voltage from grid to cathode. These elements include a source of plate voltage for the preceding tube which is not tied directly to ground, and a means of coupling the rise in potential of the cathode to this plate supply.

(8) The artificial line is the source of plate voltage for tube V2 during the pulse, and is isolated from ground by resistor R5. The only other path to ground is through resistor R9 in the cathode of tube V3. Therefore as the cathode of V3 rises during the pulse, the entire circuit of V2 is raised the same amount above ground. The drop across R6 is maintained by the discharge of the line, and is applied directly between the grid and cathode of V3. This is the bootstrap action, so-called because the amplifier raises its grid-circuit voltage in order to maintain a constant grid signal. When the artificial line is completely discharged, the voltage difference across R6 disappears, and the potential of the grid of V3 at once becomes −150 volts with respect to the cathode, and the tube is made nonconducting. The modulator tubes normally are cut off by the −1,100 volts applied to their grids through R9. The positive pulse produced across R9 drives V4 and V5 into heavy conduction, so that C16 is permitted to discharge through the magnetron to ground and through V4 and V5 in parallel. Since these tubes are in parallel, the resistors R10, R11, R12, and R13 are necessary to prevent parasitic oscillations. The charge that is lost from C16 during the generation of the r-f pulse is restored to the capacitor during the resting time by a charging current which flows from ground through diode V6, capacitor C16, and resistor R14 to the −13,000-volt supply. The diode is used as a one-way resistor which permits current to flow to charge C16, but

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which prevents loss of energy during the pulse, since none of the discharge current can flow in the diode. The use of the diode permits more efficient use of the energy stored in the capacitor because a resistor used as a charging element, as R207 in figure 80, may dissipate as much as 20 percent of the available energy during the discharge.

c. Line-controlled blocking oscillator driver. (1) A modification of the circuit of the single-swing blocking oscillator may be used to produce a pulse of accurately controlled duration for the operation of a modulator tube (fig. 138). An artificial transmis-

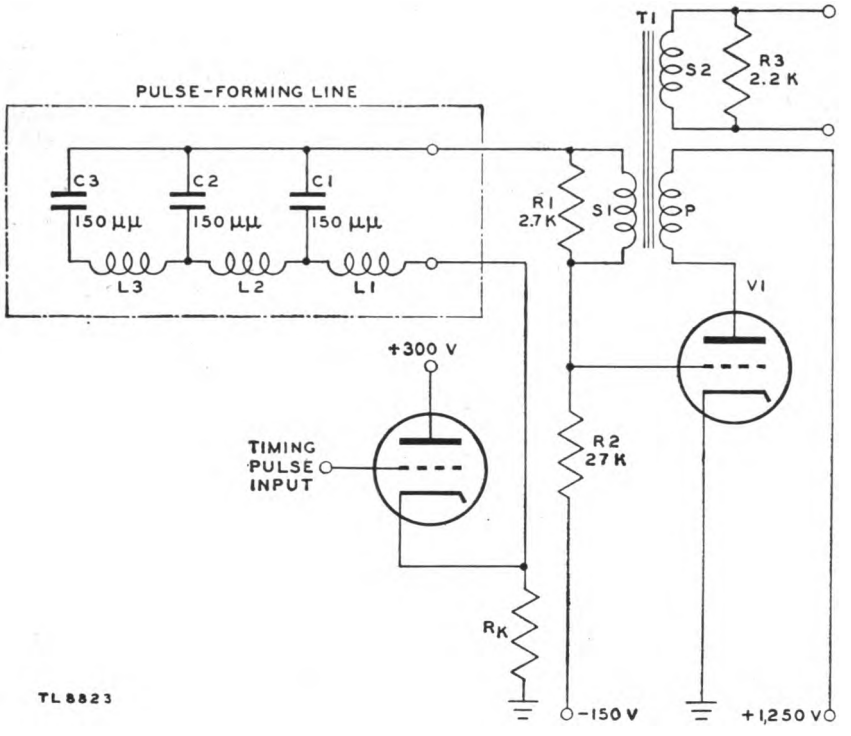

Figure 138. Line-controlled blocking oscillator: Schematic circuit diagram.

sion line is used to control the duration of the pulse, since the blocking oscillator itself is unable to produce a square output of controllable duration. One advantage of this type of driver is that it requires only one tube, which makes the driver circuit and the associated power supply simple.

(2) The blocking oscillator tube V1 is normally cut off because its grid is connected through R2 to the −150-volt bias supply. A positive timing pulse of approximately 110 volts is applied to the circuit through a cathode follower to start the operation. This pulse is coupled across the capacitance of the artificial transmission line and

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through winding S1 on the pulse transformer to the grid of V1. Although the pulse suffers considerable attenuation in passing through this network, it is of sufficient amplitude at the grid to start conduction in the blocking-oscillator tube.

(3) The plate current of V1 flows through the transformer primary, *P*, which produces a voltage across this winding. A voltage in secondary S1 is also induced that reinforces the trigger pulse, so that the grid is rapidly driven very positive as soon as conduction is started. If 1,000 volts appears across *P*, a voltage of 500 volts is induced in S1 because of the 2-to-1 turns ratio of the transformer.

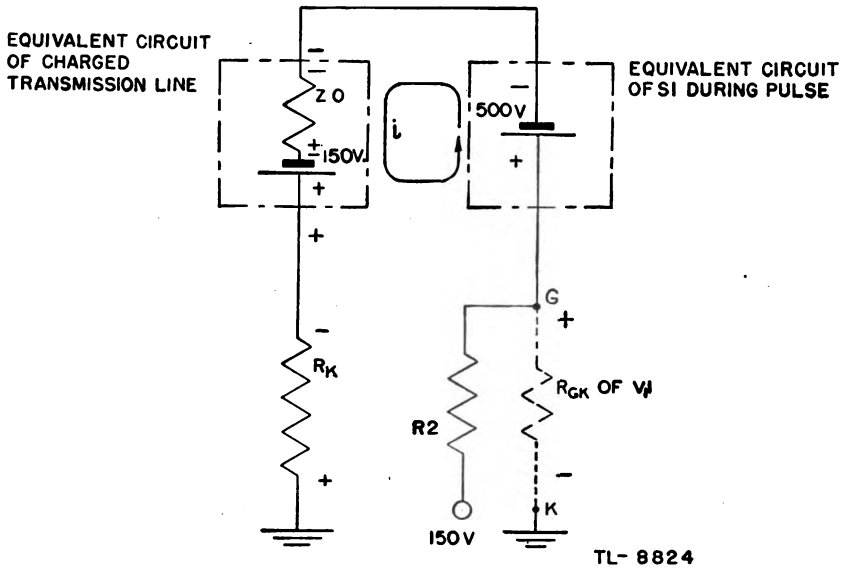

Figure 139. Equivalent circuit of line-controlled blocking oscillator.

Since the voltage induced in S1 is relatively constant during the pulse, it may be represented as a 500-volt battery with polarity as indicated in figure 139.

(4) The artificial transmission line normally is charged to −150 volts through R_k, S1, and R2 from the bias supply for V1. In the equivalent circuit, the line is shown as a resistor in series with a 150-volt battery. Since the two batteries oppose, only 350 volts is available to drive a current through the circuit. The sum of the grid-to-cathode resistance of V1 and the output resistance of the cathode follower is made equal to the characteristic impedance of the artificial transmission line. Therefore, a current i flowing in the circuit produces approximately 175 volts across the line and across the combination or R_k+R_{gk} with polarity as indicated in figure 139. As

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long as the current i continues to flow, the voltage developed across R_{gk} will keep V1 in full conduction.

(5) The additional voltage impressed on the line by the flow of current i in the circuit is of the same polarity as the initial charge. A traveling wave goes down the line, raising the voltage across it to 325 volts. When the wave strikes the open end of the line, it is reflected without change of sign. The wave then comes back toward the source, charging the line to 500 volts as it progresses. At the instant that the reflected wave reaches the input terminals of the line, the current i drops to zero, since the voltage across the transmission line equals the voltage induced in S1, at this instant making the net voltage in the circuit zero. Although the timing-pulse voltage may still exist across R_k, the potential of the grid of V1 drops sharply because of the connection to the −150-volt bias supply, reducing the magnitude of the current flowing in the tube. The duration of conduction in V1, which is equal to the output-pulse length, is controlled by the artificial transmission line. Since the line is designed so that ½ microsecond is required for the wave to travel the length of the line, the output pulse is of 1-microsecond duration.

(6) As the current in the tube starts to fall off, the voltage induced in S1 drops to zero and the artificial line begins to discharge through R2 and R_k. Both of these effects combine to drive the grid very sharply negative, which quickly cuts off the current in V1. The field set up by the primary winding must therefore collapse. In collapsing, a sharp negative surge of voltage is induced in S1 which drives the grid even farther negative. Resistor R1 is used to damp out the oscillations that are excited in the secondary by this negative surge. If no damping were provided, the positive swing of the oscillation might cause false triggering of the circuit.

(7) The waveform of the voltage at the grid of V1 is shown in figure 140①. The slight irregularities in the top of the pulse are due to the fact that the artificial line is only an approximation to a real line. The relatively slow recovery of the grid to its normal bias is caused by the discharge of the capacitors in the artificial line to their normal charge of −150 volts. The flow of current in the primary of T1 also induces a positive pulse in secondary S2. Since the turns ratio between windings P and S2 is 1 to 1, the output developed across this secondary is a pulse of approximately 1,000-volt amplitude (fig. 140②).

(8) The line-controlled blocking oscillator driver is shown in figure 141 as a component of a complete transmitter circuit. The input to the modulator tube V2 is the 1,000-volt pulse developed across winding S2 of the pulse transformer. V2 is normally nonconducting because of the −850-volt bias supplied to its control grid. Capacitor

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C5 is charged from the 14,000-volt supply through V3, R7, and L4. When the positive pulse is applied to the modulator tube, C5 discharges through the magnetron and V2, generating an r-f pulse.

(9) When the driver output pulse falls, V2 is sharply cut off. Oscillations are set up in L5 and the distributed capacitance between the magnetron filament and ground by this sudden change. The inductance is put in the circuit purposely to cause oscillations, so that the pulse at the magnetron filament may have a steep trailing edge. For example, figure 142① shows the effect of the distributed capacitance in prolonging the decay of voltage at the magnetron filament. Oscillations set up in the filament circut by the addition of inductor L5 produce a voltage of the type shown in ②. Since the negative alternations of the oscillation, as at A and B, could cause the magnetron to oscillate, the negative portions must be removed. Damping is

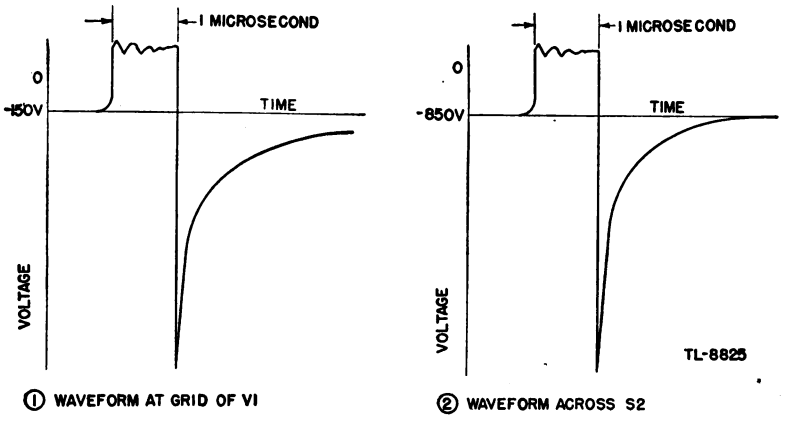

Figure 140. Waveforms in line-controlled blocking oscillator.

usually provided by a diode, so that a waveform of the type shown at ③ is produced. The diode acts as a very low resistance across the resonant circuit during the positive alternation, and quickly damps out the oscillations by absorbing the energy in the oscillatory circuit. Therefore, no negative alternations occur to cause the magnetron to operate.

(10) Because there is always a slight delay in starting the pulse in a blocking-oscillator driver, it is not desirable to use the trigger pulse for timing the rest of the radar system where short minimum ranges are important. In order to avoid the complexity that would be involved in attempting to match this delay by some form of delay circuit, a timing pulse is coupled out of the transmitter from the case of C5. Since the case of C5 is connected to one plate of the capacitor, it changes potential abruptly when the modulator is driven into conduction. Therefore, whenever the magnetron is pulsed, a negative

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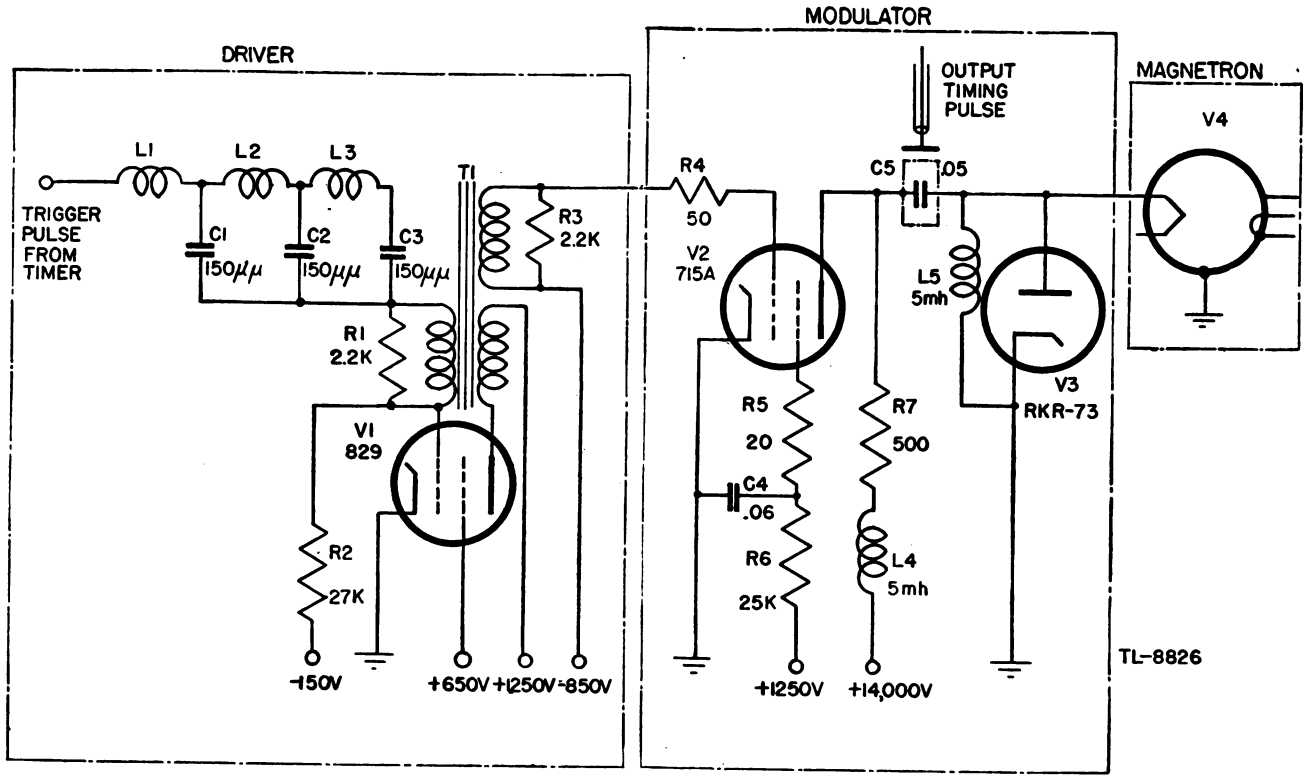

Figure 141. Schematic circuit diagram of transmitter with line-controlled blocking oscillator driver.

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C5 is charged from the 14,000-volt supply through V3, R7, and L4. When the positive pulse is applied to the modulator tube, C5 discharges through the magnetron and V2, generating an r-f pulse.

(9) When the driver output pulse falls, V2 is sharply cut off. Oscillations are set up in L5 and the distributed capacitance between the magnetron filament and ground by this sudden change. The inductance is put in the circuit purposely to cause oscillations, so that the pulse at the magnetron filament may have a steep trailing edge. For example, figure 142① shows the effect of the distributed capacitance in prolonging the decay of voltage at the magnetron filament. Oscillations set up in the filament circut by the addition of inductor L5 produce a voltage of the type shown in ②. Since the negative alternations of the oscillation, as at A and B, could cause the magnetron to oscillate, the negative portions must be removed. Damping is

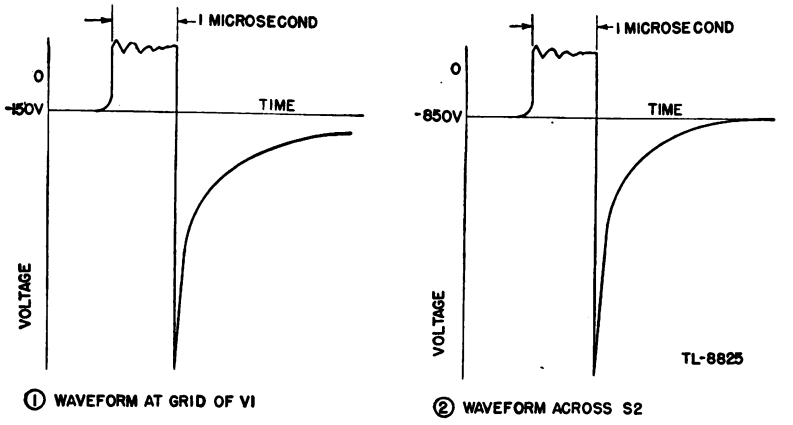

Figure 140. Waveforms in line-controlled blocking oscillator.

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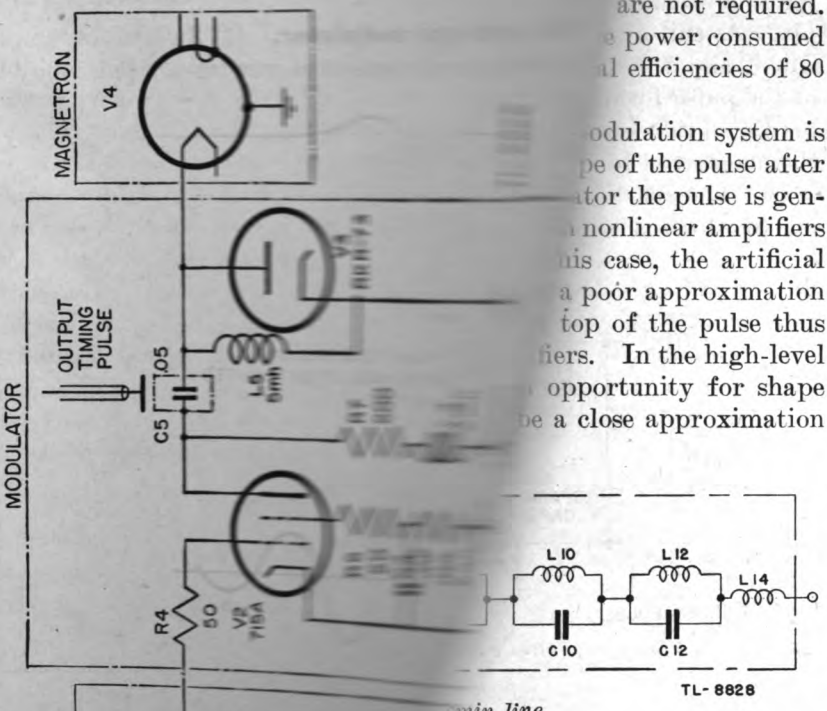

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the fixed spark-gap modulator is shown
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L1 and V1. The inductance of L1
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timing pulse is coupled out to the rest of the circuit at exactly the same instant.

d. Fixed spark-gap modulator. (1) Instead of amplifying a modulating pulse in a series of vacuum tubes, a pulse may be

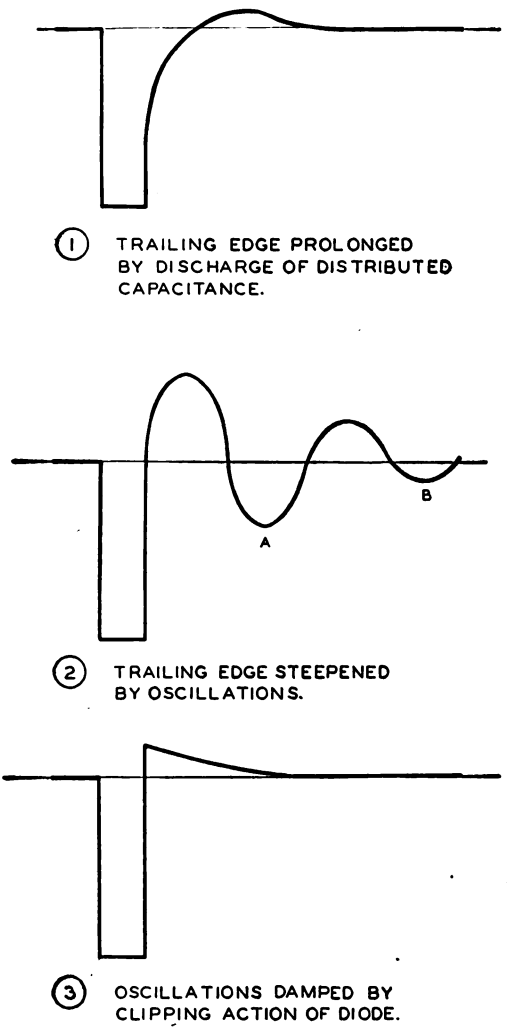

Figure 142. Modulation pulses at magnetron filament.

generated at high-power level directly by discharging a pulse-forming line through the r-f generator and a switching device. The switching device in this type of system is usually a spark gap because of the limitations on the power-handling capacity or the break-down voltage of

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other devices. The obvious advantage of this system is that modulator tubes, with their heavy filament-power drain, are not required. The spark itself dissipates very little energy and the power consumed by the auxiliary controls is small, so that theoretical efficiencies of 80 or 90 percent are possible.

(2) One disadvantage of the high-level pulse-modulation system is the fact that there is no chance to improve the shape of the pulse after it is generated. In the vacuum-tube pulse modulator the pulse is generated at low voltage and thereafter is amplified in nonlinear amplifiers which saturate at the peak of the pulse. In this case, the artificial transmission line used to form the pulse may be a poor approximation of a real line because irregularities in the flat top of the pulse thus introduced may be clipped in succeeding amplifiers. In the high-level pulse modulator, on the other hand, no such opportunity for shape correction exists. The line employed must be a close approximation to a continuous transmission line.

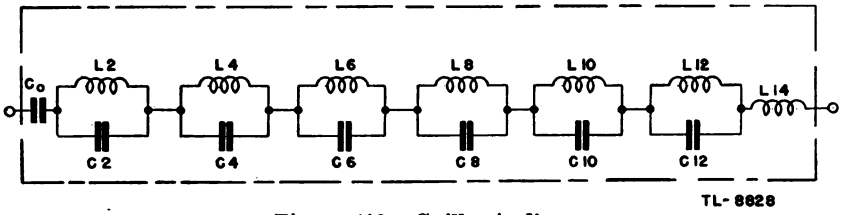

Figure 143. Guillemin line.

(3) If an artificial line is to meet this requirement, many sections must be used. Since all of the capacitors must withstand the high voltage, such a line would be very bulky. A means of reducing the physical size of the line is found in the use of the Guillemin line, shown in figure 143. The series capacitor is the only one that need be insulated for high voltage since it is the only one charged. The other capacitors are paralleled by inductances and have voltage across them only during charge and discharge, where they divide the applied voltage.

(4) When the Guillemin line is used in high-level pulse modulation, a very nearly rectangular pulse may be generated with steep rise and fall, and flat top constant within +5 percent. Modifications of the Guillemin line which use only a few sections have been developed. These networks are usually encased in a metal container filled with insulating compound, and are called "potted lines."

(5) The basic circuit of the fixed spark-gap modulator is shown in figure 144. The pulse-forming line, which may be either the Guillemin line or the ordinary artificial transmission line, is charged from the power supply through L1 and V1. The inductance of L1 and the capacitance of the line form a resonant circuit so that the volt-

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age across the line tends to oscillate. At the peak of the positive swing the line is charged to a voltage considerably higher than the d-c supply. At this instant the trigger pulse is applied to the auxiliary electrode, and the spark gap conducts. The characteristic impedance of the pulse-forming line is made equal to the impedance of the magnetron so that one-half of the voltage on the line is impressed across the magnetron for the duration of the pulse.

(6) The spark gap (fig. 145) consists of two spherical electrodes, one of which is hollow. Inserted in this hollow sphere, and insulated

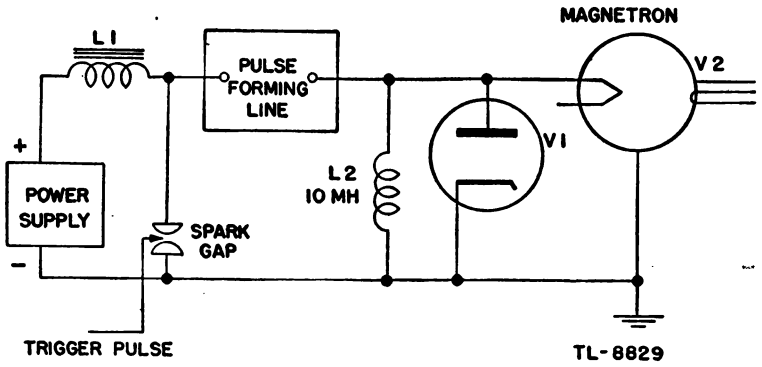

Figure 144. Basic circuit of fixed spark-gap modulator.

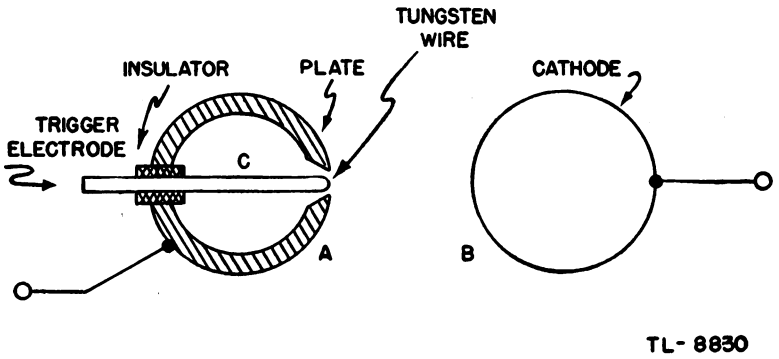

Figure 145. Fixed spark gap.

from it, is a third electrode. The main gap AB is made large enough so that the voltage between A and B will not break it down. If the gap between trigger wire C and electrode A is broken down by a trigger pulse, the resulting positive ions will be attracted toward the electrode B and will therefore cause break-down in the space between A and B. The instant of discharge can be controlled accurately in this way. Experience shows that the control of the timing of the discharge is more accurate when the hollow electrode serves as the anode, or plate, for the discharge. The spark stops when the network is

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almost completely discharged because the voltage across the gap is no longer sufficient to maintain ionization.

(7) A thyratron tube may be used in place of the fixed spark gap in the same circuit. The limitation of the thyratron is that this type of tube cannot withstand a voltage in excess of 27,000 volts, while the spark gap can be used for practically any voltage.

e. Rotary spark-gap modulator. (1) The spark gap is well suited for use in a modulator circuit because it can handle peak currents of 100 amperes or more at very high voltages. However, an arc that takes place in air produces ozone and nitrous oxide which corrode the metallic electrodes rapidly, especially in the presence of water vapor. The life of a fixed spark gap is usually less than 200 hours because of the rapid corrosion of the trigger electrode.

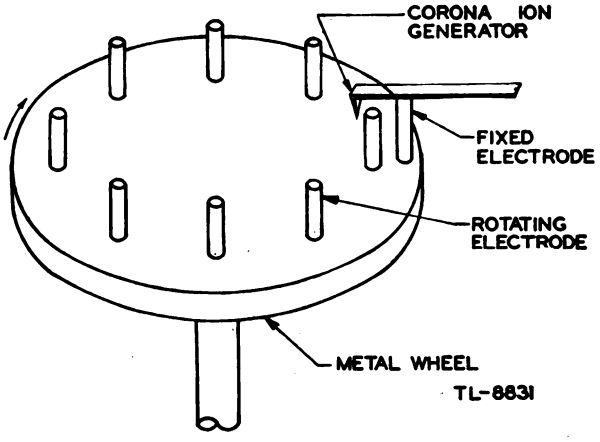

Figure 146. Rotary spark-gap.

(2) Another way of breaking down a spark gap is to cause its electrodes to approach each other at the time the gap is to fire. This can be accomplished by rotating one side of the gap on a wheel in such a way that it regularly passes a fixed electrode, as shown in figure 146. On the same bracket with the fixed electrode which serves as one terminal of the main discharge is mounted a small, sharply pointed electrode called a corona ion generator. Near the sharp point of the ion generator the voltage stress is much higher than elsewhere, so that the air is more easily ionized at the point. When the rotating electrode passes between the fixed electrode and the ion generator, the gap between the two main electrodes breaks down quickly because of the initial ionization provided by the ion generator.

(3) Since the spacing of the electrodes which form the gap is not critical, and since the corrosion of the electrodes that takes place is

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distributed among the several rotating electrodes, the life of the rotary spark gap is much longer than that of the fixed spark gap. If the corrosive gases produced by the spark are removed either by a carbon absorber or blown away by a fan, the life of the rotary gap should be in excess of 1,000 hours.

(4) Because radio-frequency energy is radiated from the spark, it is necessary to inclose the mechanism within a metal container to prevent interference with other parts of the radar circuit. In addition, chokes and filters are inserted in all leads to and from the rotary gap circuit to prevent transmission of r-f energy to other parts of the equipment. The spark gap should be kept at constant pressure in order to operate consistently. It is especially important that the pressure be maintained in aircraft installations, because the

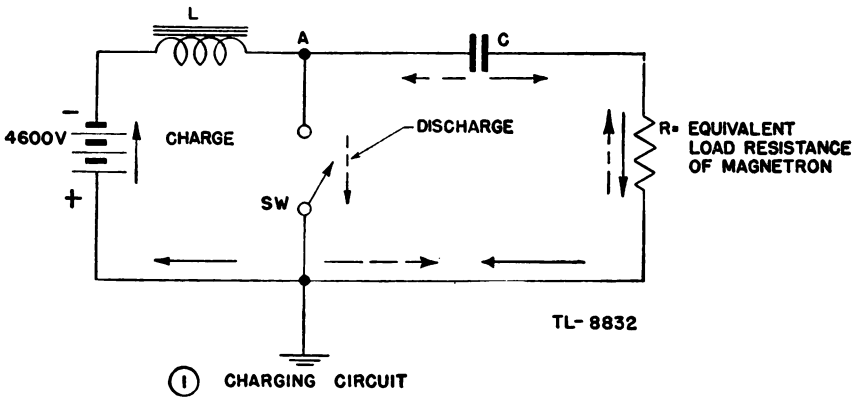

Figure 147. Equivalent circuit of spark-gap modulator.

break-down voltage of air is considerably reduced at high altitudes where the air pressure is low.

(5) The pulse-forming network used with a spark-gap modulator may be charged from either an a-c or a d-c source. Since the charge is stored on the capacitors in the network, a capacitive reactance is offered by the network during the charging time. An inductor connected in series with this capacitance produces an oscillatory circuit (fig. 147). If switch *SW* is closed sometime before t_o (fig. 148), the pulse-forming network, which is represented by *C*, will discharge through *R* and *SW* and the potential at *A* will be zero. If the switch is opened at t_o, a potential of −4,600 volts is suddenly applied to the RLC circuit. This sudden change of voltage sets up a train of damped oscillations. The initial surge of energy oscillates between the magnetic field around the inductor and the charge on the capacitor. If there were no resistance in the circuit, the current would be an undamped sine wave (fig. 148④), and the voltage at point *A* would

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vary between O and twice the applied voltage, curve ①. However, with resistance in the circuit, the voltage at point A is a damped sine-wave curve ②, which will ultimately die out, leaving the capacitor charged to the supply potential of −4,600 volts.

(6) The damping caused by the resistance in the circuit limits the first swing of voltage at point A to about −8,000 volts. The inductance is adjusted to make the frequency of the oscillation equal to one-half the pulse-repetition frequency, so that the voltage at point A will be a maximum at time t_1. If the switch is closed at this instant, the voltage at point A falls to zero (curve ③), and the pulse-forming network discharges through R. Since R is equal to the characteristic impedance of the network, a pulse of 4,000-volt amplitude is produced across it by the discharge.

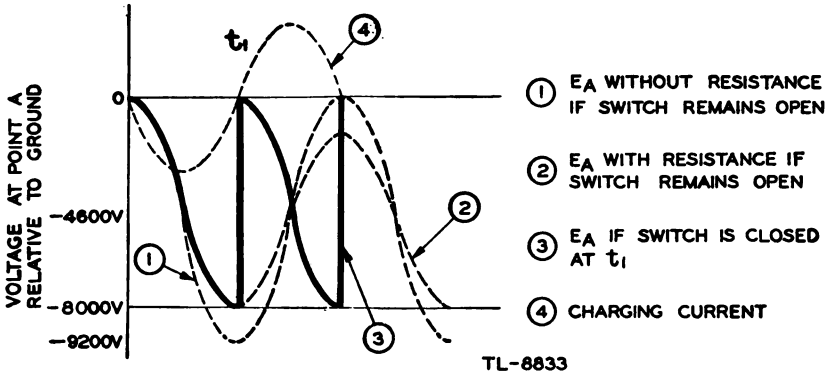

Figure 148. Capacitor charge and discharge.

(7) The exact instant of striking the arc in a rotary spark gap is not easily controllable and the arc may not strike at exactly t_1 for every pulse. Although the voltage at point A does not change greatly within several microseconds before or after t_1, is is sometimes desirable to connect a diode in the circuit to prevent this voltage from decreasing (fig. 149). The diode permits electrons to flow in the direction for charging the network, but at t_1 when the current attempts to reverse direction (fig. 148④), the diode becomes nonconducting and prevents any further change of charge on the network. By this means, the network can be charged to nearly twice the applied voltage, and as it will remain at this voltage there is no need of synchronizing the firing of the spark gap with the period of the charging oscillation.

(8) The pulse-forming network may be charged directly from a transformer when connected in a circuit similar to that shown in figure 150. In this case the circuit is not resonant, but the frequency of the applied power corresponds to the d-c resonance charging of the type previously discussed. The same variations in the basic circuit can be made.

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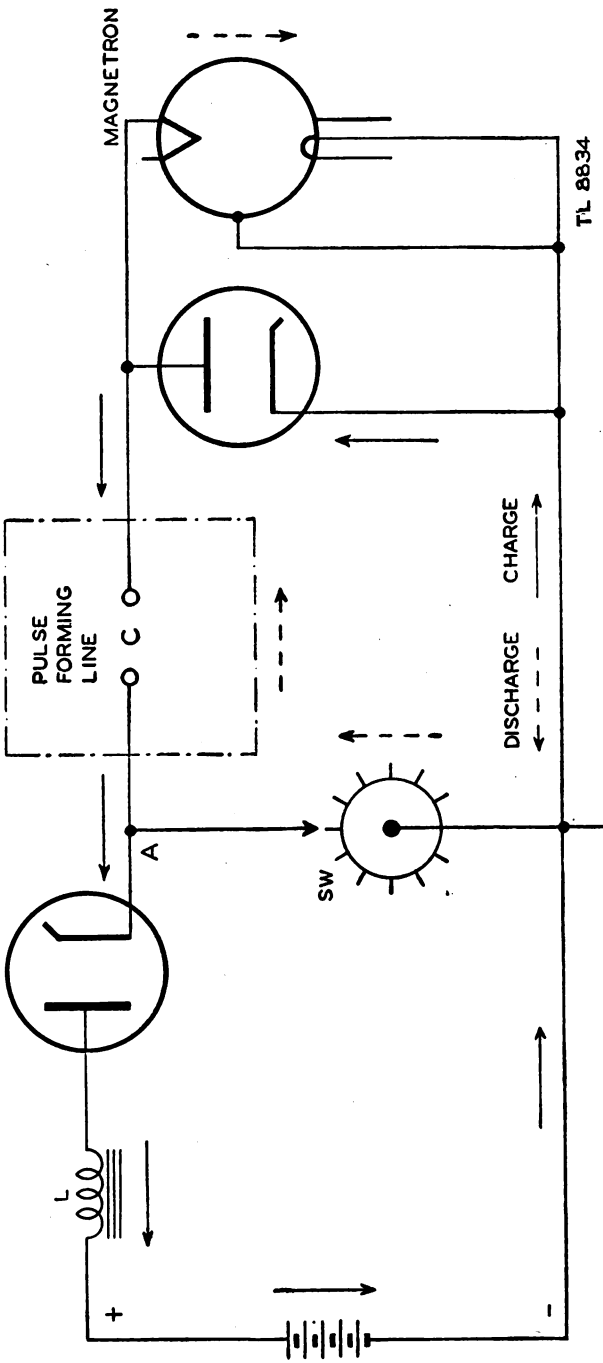

Figure 149. Charging diode in rotary spark-gap modulator circuit.

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(9) Improvement in the performance of spark-gap modulators can be had by using transformers which are specially designed to pass a pulse waveform without introducing substantial changes in its shape. Such transformers serve several important purposes in modulator equipment. In the first place they may be used to change the impedance level in pulse circuits, changing from a high-voltage, low-current source to a low-voltage, high-current output, or vice versa. In the

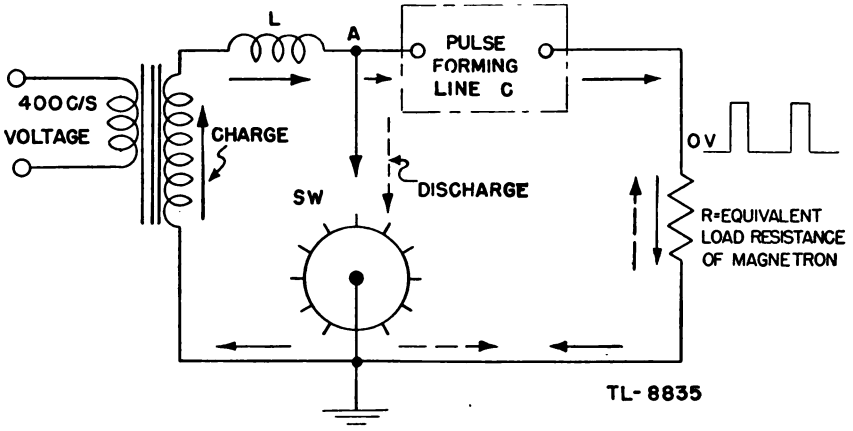

Figure 150. A-c charging through inductance.

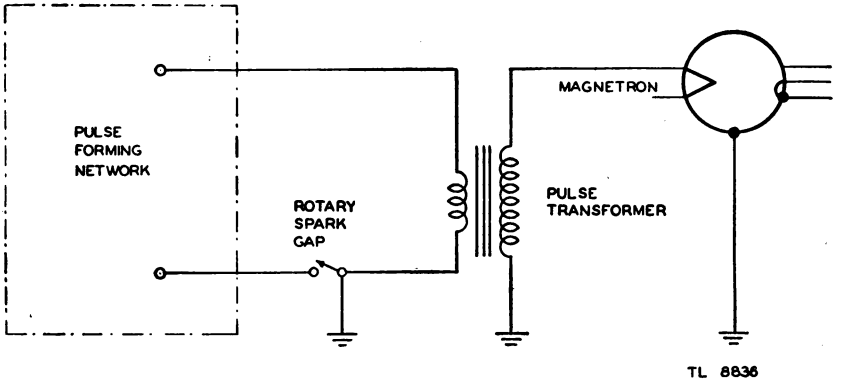

Figure 151. Pulse transformer in spark-gap modulator circuit.

second place, the transformer may be used as a polarity reversing device, as in the blocking oscillator discussed in paragraph b above. In the third place, the transformer may serve to isolate d-c sources.

(10) The most common use of the pulse transformer is illustrated by figure 151. The pulse is formed by a rotary gap discharging an artificial line through the primary of the transformer. The turns ratio is such as to step up the primary voltage to a much higher value to be applied to the magnetron. Since the magnetron impedance as seen

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by the line is stepped down as well, the pulse-forming network need not be built to withstand the high voltage of the pulse reaching the magnetron, and can have a lower characteristic impedance. The voltage of the power source for charging the pulse-forming line is correspondingly smaller.

(11) In many radar installations, particularly those in aircraft, it is desirable to separate the antenna and the bulky power units of the transmitter by a considerable distance. This can be accomplished by running a long coaxial line or waveguide from the magnetron to the antenna. However, long r-f lines tend to make the operation of the magnetron unstable and such long lines should be avoided if possible. An alternative to long r-f lines is to separate the magnetron from the modulator and power supplies, and to connect them by a long cable (fig. 152). It is necessary to terminate the pulse cable in its character-

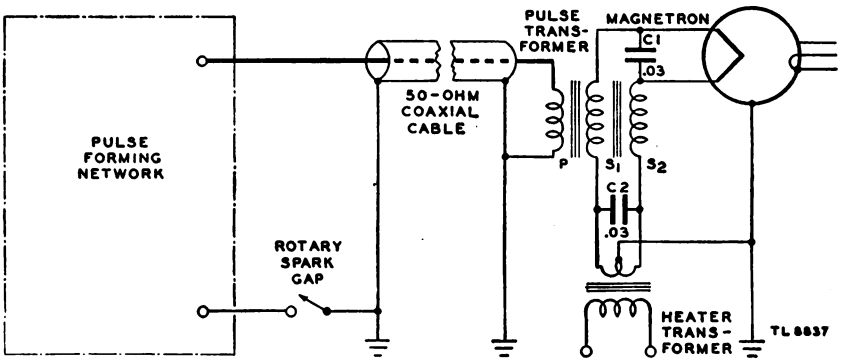

Figure 152. Separation of magnetron and modulator circuits, using 50-ohm coaxial cable and pulse transformer.

istic impedance to prevent reflection of the pulse. Since it is impractical to build a coaxial line of which the characteristic impedance is equal to the static resistance of the magnetron (about 800 ohms), the coaxial line must be terminated in a pulse transformer. The pulse transformer and magnetron are not bulky, thus it is feasible to have them near the antenna.

(12) Two secondary windings are wound on the pulse transformer. When a pulse is applied to the primary, the voltage induced in each winding is negative at the cathode end of the coils. The two secondary windings are effectively connected in parallel for the pulse voltage by capacitors C1 and C2, so that both windings aid in driving current through the magnetron. With two secondary windings connected in this way, the lower ends are nearly at ground potential. Therefore the heater transformer need not be insulated for high voltages. This connection permits the use of conventional heater transformer in this

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circuit instead of the special transformer, insulated for the full pulse voltage, that was required in the transmitter discussed in section IV.

(13) In figure 153 is shown the circuit diagram of a complete rotary spark-gap modulator and transmitter. The pulse-forming network is charged to 8,000 volts from a voltage doubler through a resonant-charging circuit consisting of L1, V1, Z1, L2, R2, R3, and the primary winding of T1. Although most of the discharge current flows through the primary of the pulse transformer, some of the current flows through R2 and R3 and through L2. The output of the modulator is a positive-going 4,000-volt pulse. Therefore, a positive pulse of approximately 125-volt amplitude is developed across R3 to be used as the timing pulse for the rest of the system.

(14) The 4,000-volt positive pulse in the primary of the pulse transformer induces a negative 18,000-volt pulse in the secondary windings. Should the load be removed by disconnecting the magnetron, a voltage much larger than 18,000 volts would be developed across the secondaries because of the poor regulation of the transformer. To prevent damage to the transformer from the possible high voltage, a protective spark gap, adjusted to fire at 25,000 volts, is connected across one of the secondaries. Should the gap fire, the transformer would be heavily loaded, and the voltage could rise no higher.

(15) The pulse voltage induced in the two secondary windings of the transformer is equalized by bypass capacitors C1, C2, and C4. Since it is desired to keep the lower ends of the two windings nearly at ground potential, capacitors C1 and C2 are connected to ground. The magnetron plate current passes through the magnetron to ground, through R4 and C3 in parallel, and the pulse transformer secondaries. The voltage developed across R4 is proportional to the average current flowing in the magnetron and the damping diode because C3 filters out the surges. If it is desired to have an approximate indication of the magnetron-plate current, a meter may be connected across R4. If no meter is desired, the circuit may be simplified by the elimination of the bypass capacitors, and the center taps of the heater transformers may be grounded to provide a closed circuit for the plate current.

f. Saturable inductor modulator. (1) Instead of producing a low-power pulse and amplifying it, or generating a high-power pulse from an artificial line, a saturable inductor can be used as a switch to control the charge and discharge of a network to produce an approximately square modulating pulse. The block diagram of such a system is shown in figure 154.

(2) The timing input to the current control tube is a square wave. During the positive portion of this square wave, V1 is conducting, and energy is stored in the field around inductor L1. When the tube is

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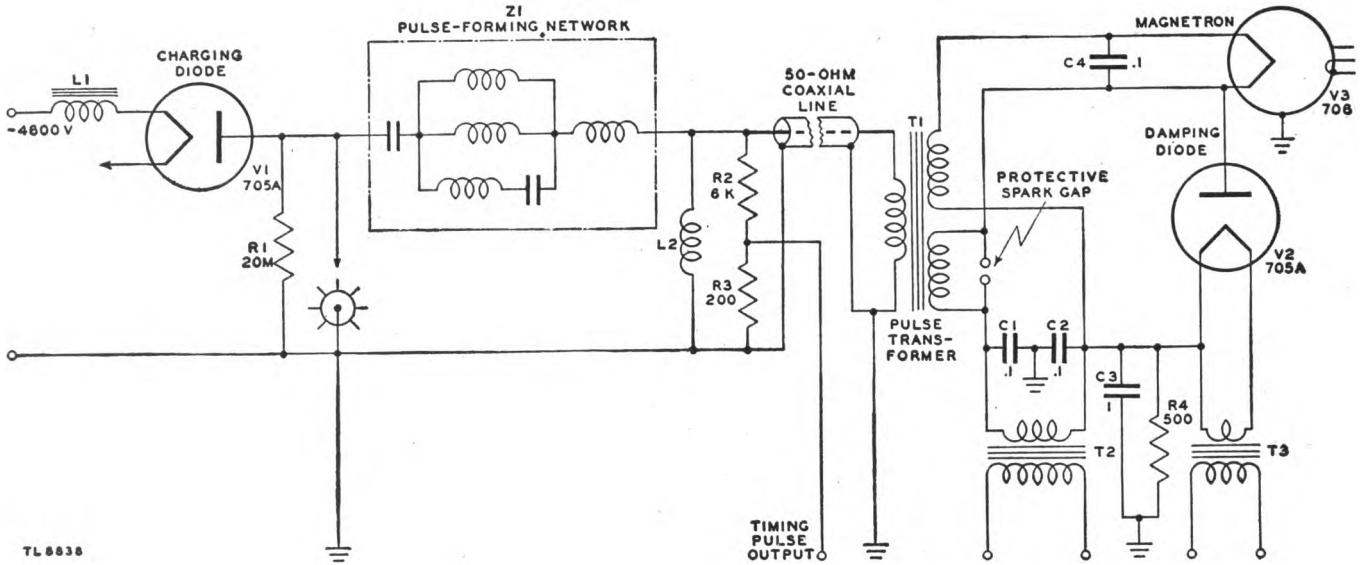

Figure 153. Schematic circuit diagram of complete rotary spark-gap modulator and transmitter.

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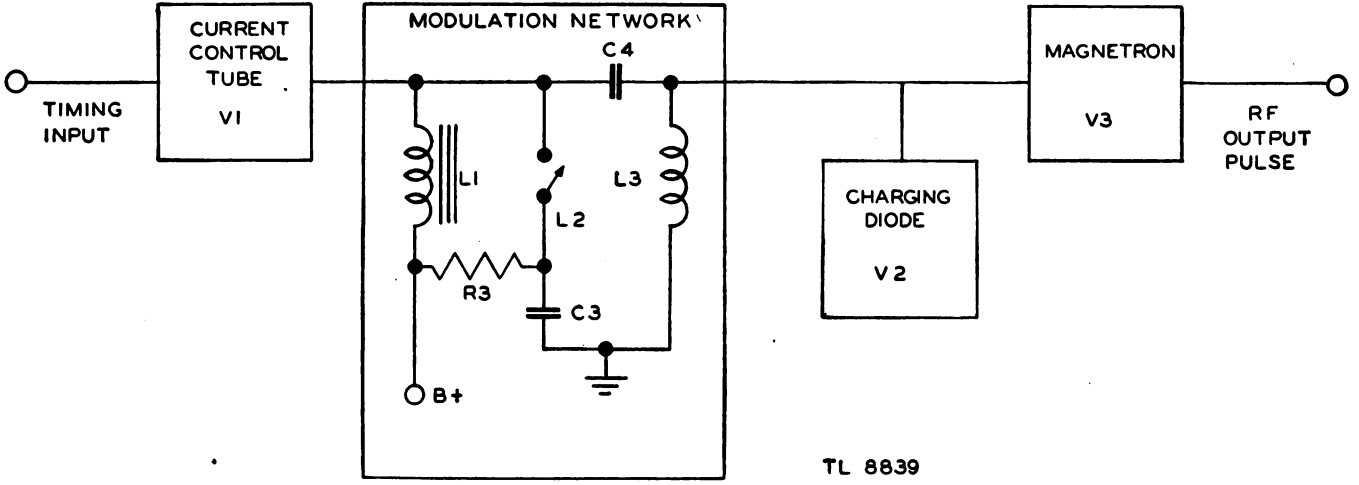

Figure 154. Block diagram of saturable inductor modulator.

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cut off, this field collapses, charging capacitor C4 through the charging diode. At the instant that the voltage across the capacitor is a maximum, the saturable inductor switch, L2, is closed and the capacitor voltage is applied across the magnetron through C3.

(3) A saturable inductor can be used as a switch since it can be either a very high impedance or a very low impedance, depending on the conditions under which it operates. This wide change of impedance is possible because the core of the saturable inductor, or nonlinear coil as it is sometimes called, is saturated by a relatively low current in the coil. A graph, called a magnetization curve, in which the flux density in the core is plotted against the current in the coil, is shown in figure 155. The horizontal portions of the curve are called the saturated region because a current more positive than *A* or more negative than *B* cannot cause an increase in the flux density in the core. In the region between *A* and *B* the flux density in the core is

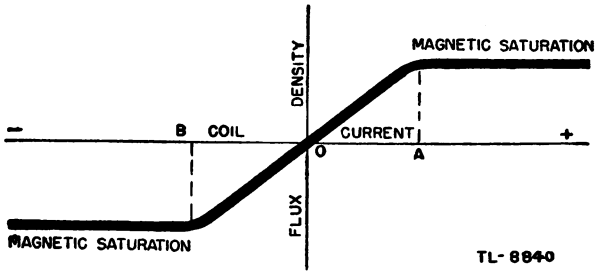

Figure 155. Magnetization curve of saturable inductor.

directly proportional to the current flowing in the coil. Since the voltage across an inductor is proportional to the rate of change of the magnetic flux that links the coil, no voltage appears across it when the core is saturated, even though the current may be changing. With zero voltage across the inductor, it acts as a short circuit; with a voltage induced in the coil by a changing magnetic field, it acts as an impedance which is made high by proper design of the coil. Therefore, when the current through a saturable inductor lies in the region between *A* and *B*, it may be considered as an open switch; when the current is beyond either *A* or *B*, the inductor is a closed switch.

(4) A schematic circuit diagram of a modulator which uses a saturable inductor as a switching devise is shown in figure 156. Note that the symbol for the saturable inductor, L2, is similar to the symbol for a conventional inductor with a line through it to represent its magnetization curve. The current control tube V1 is normally cut off by grid-leak bias developed by C1 and R1. When the timing square wave swings the grid of V1 positive, current i_1 and i_2 begin to flow in plate load inductors L1 and L2. Current i_2 quickly builds

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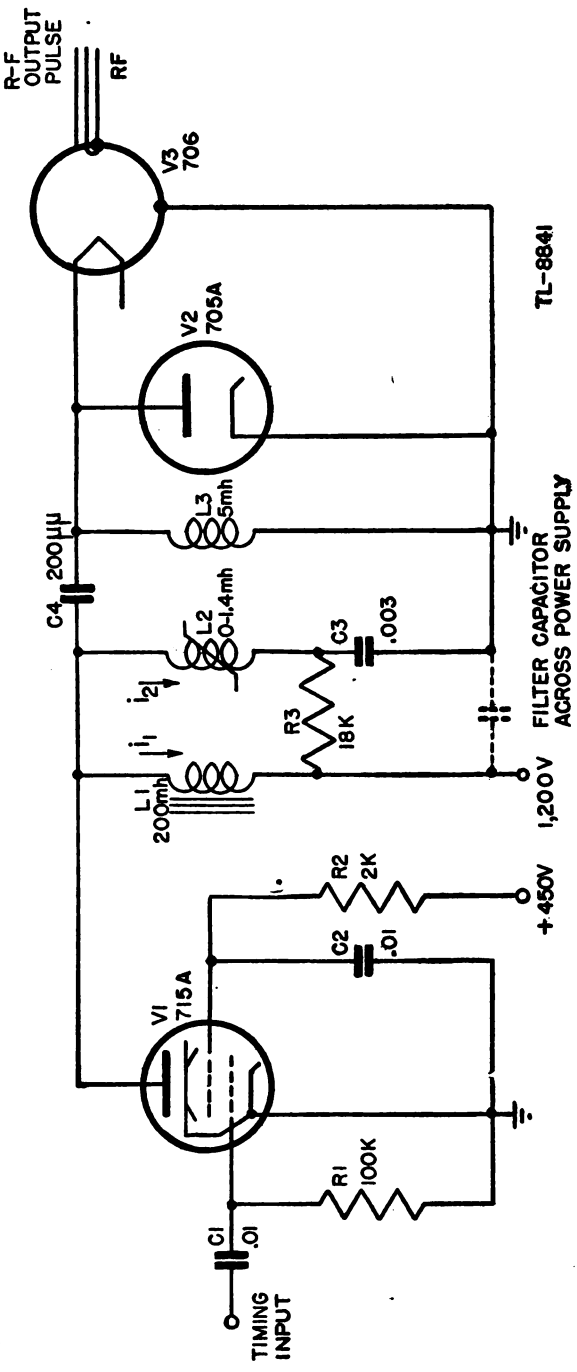

Figure 156. Schematic circuit diagram of saturable inductor modulator.

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up to a value in excess of saturation value, so that L2 becomes a low impedance.

At this time, C3 quickly discharges through L2 to the voltage at the plate of V1. Although L2 offers very little impedance to a further change of current in this branch of the circuit the magnitude of i_2 is limited by resistor R3. Inductor L1 is shunted by a high impedance, whether L2 is saturated or not, so that most of the plate current of V1 must flow through L1. As the current i_1 continues to increase, energy is stored in the magnetic field around L1.

(5) When the current-control tube is cut off by the negative swing of the timing square wave the field around L1 starts to collapse. A high voltage with polarity as shown on L1 is induced across L1 by the collapsing field. This voltage is momentarily short circuited by the low impedance of L2, C3, and the filter capacitance across the 1,200-volt power supply, tending to reverse the direction of flow of i_2. When i_2 decreases to saturation value, L2 becomes a high impedance, At this instant, the energy of the collapsing magnetic field begins to be transferred to capacitor C4 in an oscillatory transient. As energy is transferred to C4, the voltage across it builds up along a sine curve. This voltage reaches a maximum of about 15,000 volts, with the polarity shown in figure 28, in approximately 10 microseconds, which is equal to a quarter of the period of the oscillation of the resonant circuit made up chiefly of L1 and C4. The path through which capacitor C4 is charged from L1 is through diode V2 and the filter capacitance across the 1,200-volt power supply.

(6) While capacitor C4 is being charged, current i_2 in the saturable inductor decreases from saturation value A to zero and builds up toward saturation value B in the other direction. The time required for this reversal to take place is approximately 10 microseconds. When L2 again is saturated, it becomes a low impedance, grounding the positive side of C4 through capacitor C3. Since the capacitance of C3 is about 15 times greater than that of C4, and since L2 is a low impedance, approximately 14,000 volts appears across the magnetron. The polarity of the voltage on C4 is such that the magnetron cathode is made negative with respect to the anode, causing oscillation.

(7) Initially inductor L3 is a very high impedance to the discharge of capacitor C4, because the current in the inductor cannot change instantly. However, after about 0.3 microsecond, the current through this inductor has built up to an appreciable magnitude, and L3 effectively shunts the magnetron with a constantly decreasing impedance. Since the impedance of L3 becomes low, the rate of discharge of C4 is increased, causing the magnetron to go out of oscillation quickly. Within the 0.3-microsecond period oscillations of a single mode are produced by the magnetron in spite of the fact that the

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plate voltage decreases from 14,000 volts to approximately 8,000 volts during this time. Although it was pointed out that the voltage impressed on a magnetron should be constant to prevent oscillation in undesired modes, it is possible to operate improved magnetrons with the type of voltage provided by the saturable inductor modulator without harmful loss of power.

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Section VII
Antenna Systems

36. INTRODUCTION.

a. General. Previous sections of this manual have indicated that the electrical characteristics and physical appearance of radar antenna systems may vary widely. The approximate size of the antenna is determined by the selection of the carrier frequency and the type of installation. The actual design for a given equipment is based on several considerations which control the over-all efficiency and the angular accuracy of the data to be obtained.

b. Efficiency considerations. (1) Maximum efficiency of the antenna system demands that each link in the path from transmitter to antenna, and from antenna to receiver, waste as little of the r-f energy as possible. The transmission line used should therefore have the smallest possible losses, consistent with the physical types, which can be used for a reasonable size of unit.

(2) In addition to protecting the receiver circuits from burnout and blocking, the T-R switch increases the energy transfer by guiding the signals to their proper destination. During the transmitted pulse the receiver path is closed, and during the resting time the transmitter path is closed. Thus, in each case, the energy is used to produce the desired result, without wasting power in inactive circuits.

(3) Finally, the over-all efficiency can be raised if the particular application for which the system is to be used will permit concentration of the energy into a narrow beam.

c. Angular accuracy. (1) The ability of a radar unit to locate targets in azimuth or elevation depends on how well the antenna can select the direction of the return signal. It has been shown in section I that a narrow beam is better able to find the maximum return-signal direction than a wide one. Double lobe systems still further increase the accuracy of angular measurement.

(2) Back radiation and side lobes tend to confuse the operator, and therefore to decrease his ability to locate targets. Antenna construction which will reduce unwanted lobes in antenna patterns is usually employed to aid in this respect.

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37. ANTENNA FEED SYSTEMS.

a. Two-wire open line. (1) The simplest form of transmission line to construct is the two-wire line. Characteristic impedances from 150 ohms to 1,000 ohms are easily obtained. The most common form uses wires or tubing which are accurately spaced by means of ceramic insulators.

(2) At extremely high frequencies the insulators lose some of their insulating qualities, and leakage currents across them waste power. When the transmission line is made resonant, the leakage current may

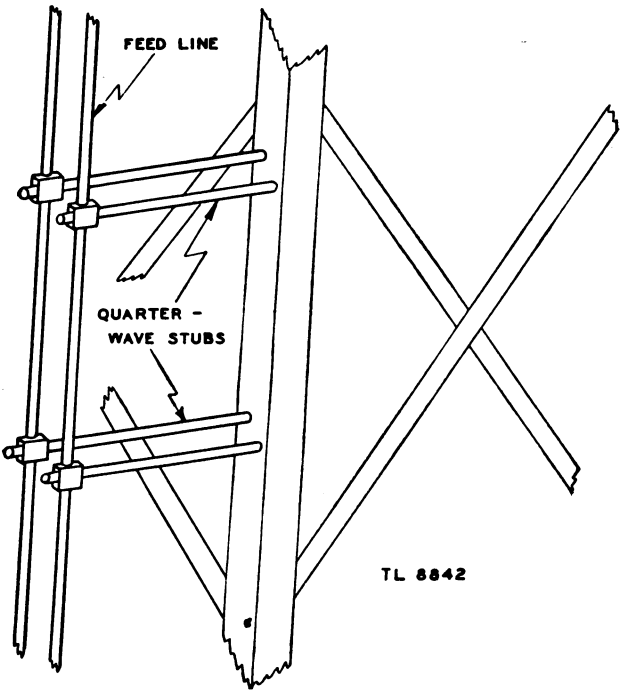

Figure 157. Stub supports for an open-wire line.

actually heat and crack the ceramic. Placing the insulators at voltage nodes, and making use of a better material, such as polystyrene, will sometimes reduce losses to a reasonable point.

(3) A much more satisfactory form of insulator is the stub support. This is simply a quarter-wave transmission line short-circuited at one end. The other end presents a very high impedance to any outside circuit. Stub supports can be applied in many ways. Figure 157 illustrates the use of two solid rods fastened to the side of a tower to support a transmission line running up to the antenna. The stub lengths are $\lambda/4$ and the tower forms the shorting bar. For purposes of mechanical strength, the feed line may be connected to the support at some distance from the open end. This is possible with low-loss

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stubs since their impedance is very high at the open end, decreasing to zero at the tower. The connection point is selected to give a sufficiently high impedance to avoid changing the much lower impedance of the feed line.

(4) Figure 158 shows a method of support within the operating building consisting of two tubes of the same size as the main transmis-

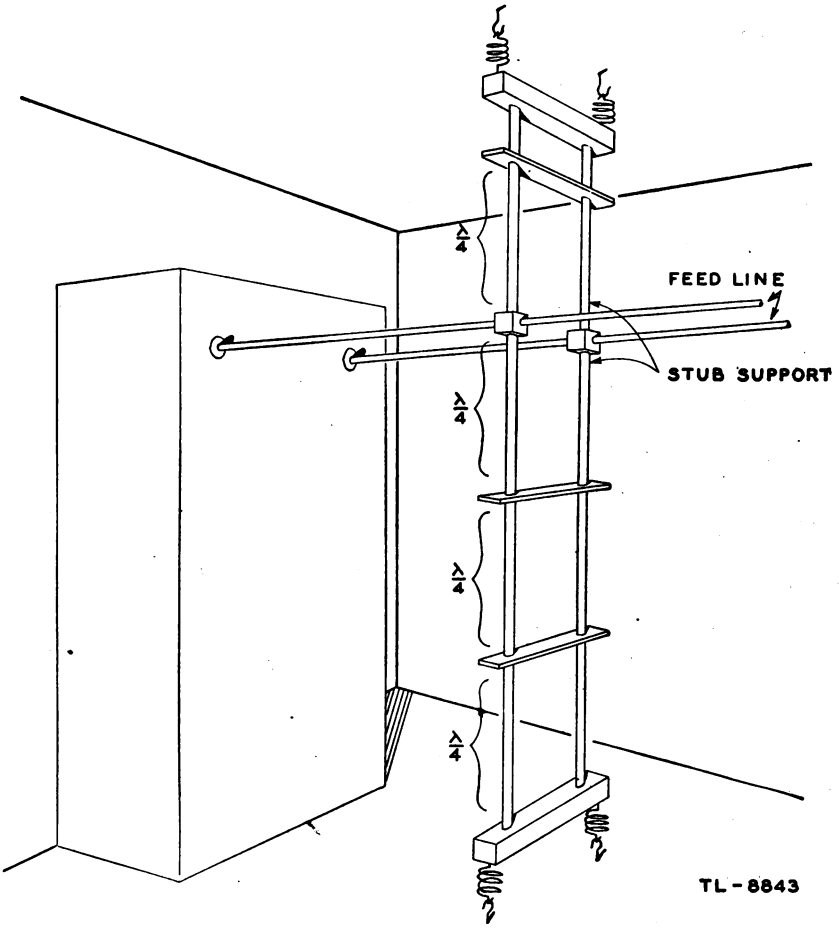

Figure 158. Tension support.

sion line which are stretched from ceiling to floor. Shorting bars are placed a quarter-wave above and below the feed line to present a high impedance across it. Additional shorting bars are placed a quarter-wave apart to prevent the supporting line from absorbing power from the main feed line.

(5) Open wire lines are easy to construct and maintain, and in addition are relatively inexpensive. The process of matching to both the

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antenna and the transmitter is simple, since matching stubs can be placed anywhere on the feed line. Rotating joints generally take the form of concentric loops formed across the line to obtain inductive coupling from one side to the other. The main disadvantage to the open-wire line is that, because of the spacing between conductors, the feed lines will radiate, which results in an increase in losses. The higher the frequency the greater are the losses.

b. Coaxial lines. (1) The coaxial line has the main advantage over the open-wire line of being completely shielded. The energy is conveyed entirely within the outer conductor, so that none of it is radiated and lost. At extremely high frequencies the saving in power is considerable. In addition, the space occupied by the installation is small, and the method of mounting is very simple, since the outer surface is at ground potential.

(2) The inner conductor of the coaxial line is normally centered in the outer conductor by means of ceramic or polystyrene spacers. Just as in the open-wire line, the insulators become partial conductors in the microwave region. In some lines special spacing of the insulators has been used to minimize losses. The more practical method is the use of stub supports as employed in the radar system described in section IV. Figure 81, *B*, illustrates the coaxial stub support.

(3) The disadvantages of the coaxial line are not great enough to prohibit its use, but should be considered. Since the outer conductor completely incloses the inner, the use of stub matching is complicated. Where necessary, two stationary stubs, adjustable in length, are used instead of the single stub which can be adjusted in length and position. The peak power of the transmitted pulse is high enough so that the spacing of the conductors must be relatively large to avoid arc-over and damage. It is general practice to seal the line and fill it with inert gas to increase the break-down voltage. This has the added advantage of preventing the collection of moisture which will lower the break-down point. The connection to an antenna is normally balanced to ground, while the coaxial line has one grounded side, which results in the need for a balance converter, or bazooka.

c. Waveguides. (1) The losses in a coaxial line become excessive at wavelengths shorter than 10 centimeters. Fortunately the waveguide can be constructed in a reasonable size for use at these wavelengths. The largest dimension in cross section is normally 3 inches for 10 centimeter waveguides, while those for 3 centimeters are correspondingly smaller. The losses are much smaller than for coaxial lines, and waveguides have the additional advantages of simplicity in construction and no need for gas filling.

(2) Section XI, TM 11-466 and Navships 900,016 explains the theory of the waveguide, the types which may be used, and the modes

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in which they may be excited. The methods for coupling energy into and out of waveguides are also discussed. Both the rectangular and round waveguides are used extensively. Generally speaking, the rec-

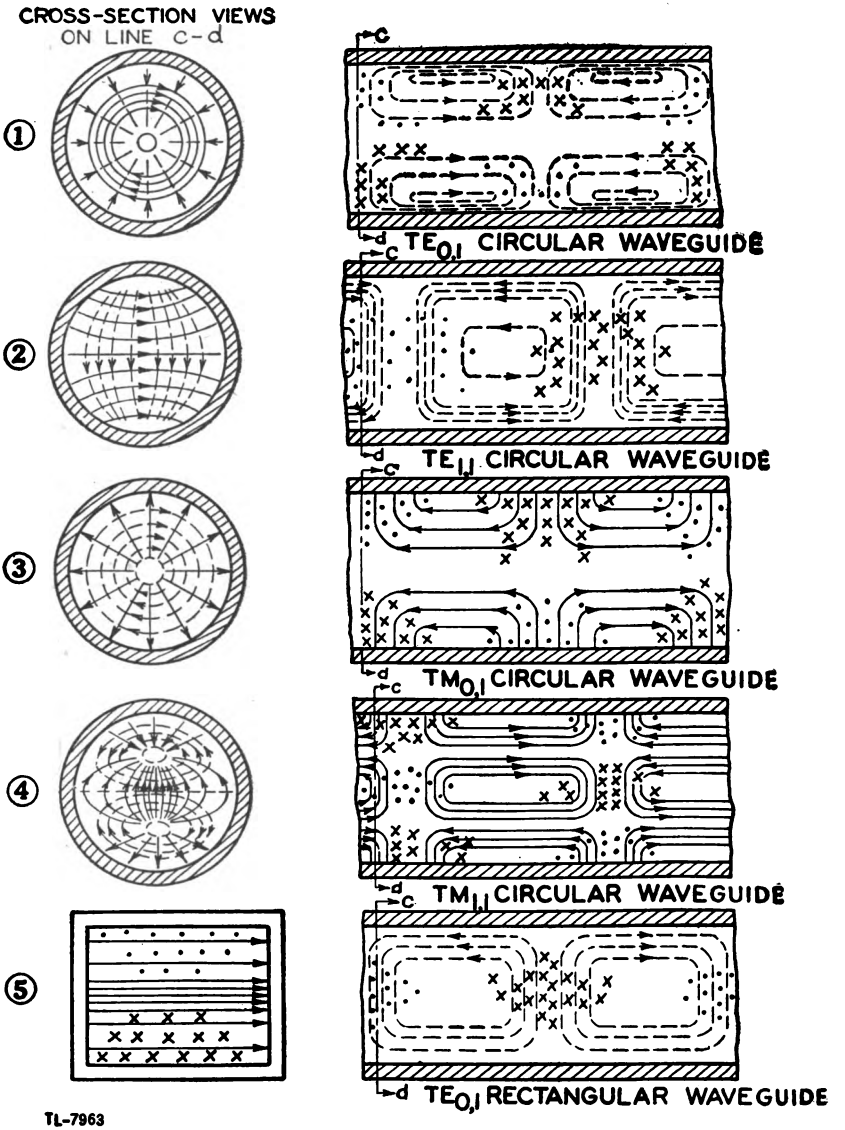

Figure 159. Common modes of waveguide excitation.

tangular type have less losses than the round, but the round waveguide is very useful in the construction of a rotating joint of simple design. The mode of excitation has considerable effect on the losses which occur, and as a result there are three modes which are most

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commonly used. Figure 159 showe these modes. Of the two circular modes, the $TM_{0,1}$ has the greater losses, but it will maintain the polarization of the wave in passing through a rotating joint, and is therefore used quite often.

(3) The use of waveguides in the antenna system involves the problems of coupling energy from the r-f generator into the guide, allowing for expansion of the system as the result of temperature changes, rotating of the antenna for searching, and supplying of the power to the antenna proper. In the discussion that follows, several possible waveguide systems will be explained in order to bring out specific problems and their solution. The illustrations are applications of the material described in section XI, TM 11–466 and Navships 900,016.

(4) Figure 160 shows a complete antenna system using both circular and rectangular waveguides. The magnetron supplies its output to a coaxial line through a small coupling loop formed by the inner conductor of the line. The line is then connected to the waveguide so that the inner conductor passes through, and perpendicular to, the wide face. The line is extended to end in a short-circuiting plunger, which is adjusted to cause a voltage maximum in the waveguide, approximately a quarter-wavelength away. Maximum output of the magnetron is produced by means of the matching stub.

(5) The waveguide is excited in a $TE_{0,1}$ mode, the guide plunger serving to control the actual coupling by adjusting the standing waves in the guide. A 2¾- by ⅜-inch guide is used near the magnetron for compactness, but to increase efficiency of transmission this is expanded to a 3- by 1½-inch guide above the transmitter. Near the rotating joint, the rectangular guide is changed to a 3-inch circular guide, which is excited in the $TE_{1,1}$ mode. An expansion joint is formed above this point by breaking the circular guide. A choke, consisting of a flange on either side of the break, prevents radiation and loss of energy. The side slots of the choke are a quarter-wave in depth, and less than $\lambda/10$ in width, so that they form resonant circuits which will present an open circuit at the outer edges of the flanges. The open circuit is reflected to the guide a quarter-wave away as a short circuit, bridging the gap electrically. The short circuit is maintained by the side slots as the expansion joint is opened or closed.

(6) The rotating joint is similar in principle to the expansion joint except that the gap between sections is fixed, and one section turns with respect to the other. Since the gap is fixed, the choke is simpler than for the expansion joint. Two flat flanges are attached on either side of the break, with a fixed spacing of less than $\lambda/10$. The flanges form the two sides of a quarter-wave line which is open-circuited at the outer end. The energy in the guide sees this high impedance reflected as a short circuit which confines the energy within the guide.

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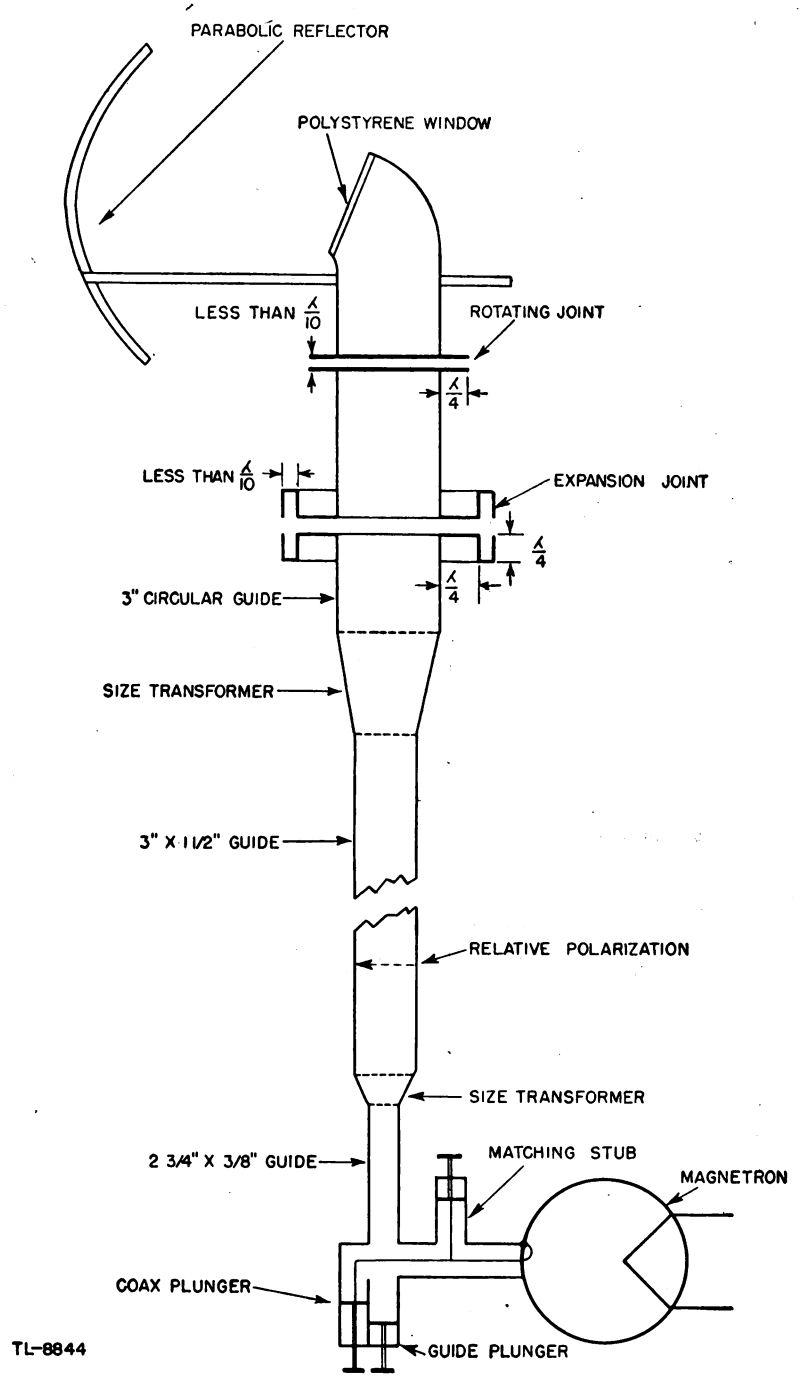

Figure 160. Waveguide antenna system.

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(7) The 3-inch circular guide is continued up to the antenna, where a gentle bend in the guide directs the r-f energy at a parabolic reflector. The waveguide terminates in a polystyrene window placed at the focal point of the reflector. Maximum radiation through the polystyrene is insured by selecting its dimensions to match properly the characteristic impedance of the waveguide to that of the reflector and free space. The electric field is transverse in the circular guide ($TE_{1,1}$) so that in passing through the rotating joint the energy may undergo a change in relative polarity. As shown in figure 160, the electric field is horizontal below the rotating joint, but is turned and becomes verti-

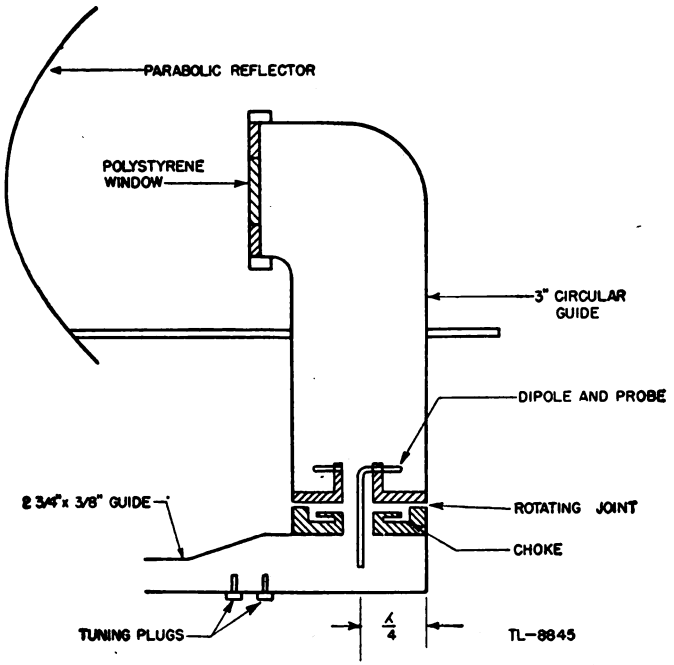

Figure 161. Coaxial rotating joint.

cal in reaching the reflector. If the antenna is rotated 90°, so that it points out of the page, the electric field passes up the guide without change and the polarization is horizontal. At other angular positions of the antenna the polarization will vary between horizontal and vertical. This is the main difficulty encountered in using a circular guide excited in the $TE_{1,1}$ mode as a rotating joint.

(8) Constant vertical polarization of the radiated energy can be maintained if the feed system is modified to use a short section of coaxial line as the rotating joint (fig. 161). The coaxial line is used to couple a rectangular guide to a circular guide. The rectangular guide is terminated in a slightly larger section which is shorted at the end. Two tuning plugs serve to adjust for an impedance match to

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secure maximum energy transfer. The coaxial line has its inner conductor extended into the rectagular guide as a voltage probe, and into the circular guide as one-half of a dipole. The outer conductor is extended about a quarter-wave into the end of the circular guide, and has the other half of the dipole fastened to it. The rotating joint is formed by breaking the outer conductor and using a choke to bridge the gap. The choke slot is bent back on itself and has a total

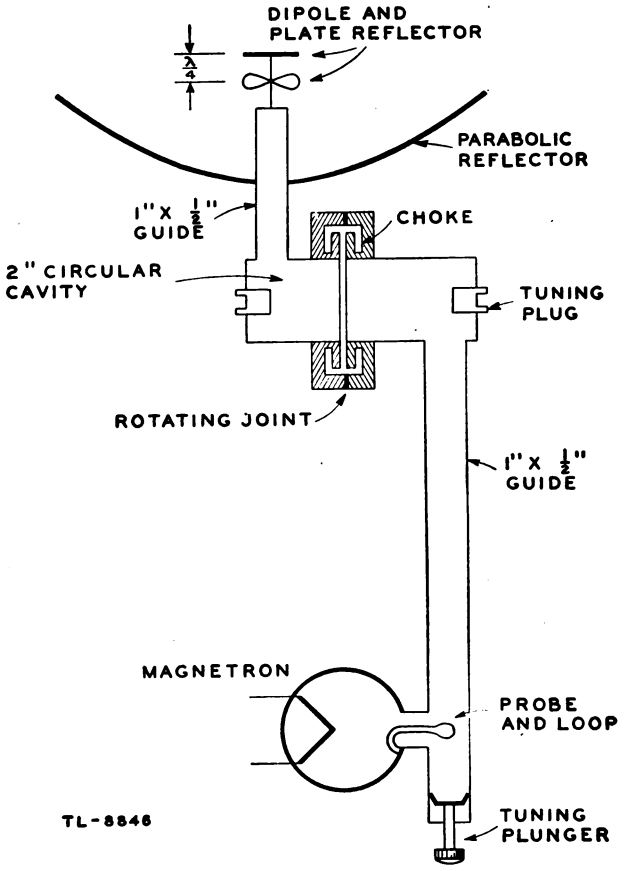

Figure 162. Rectangular guide antenna feed.

length of a half-wave, so that the short at the end of the slot is reflected as a short across the gap of the joint. Polarization is established by the position of the dipole in the circular guide, and is not changed by rotation, since the dipole moves with the guide.

(9) Figure 162 illustrates an antenna system suitable for 3 centimeter wavelengths which has several differences from those previously discussed. The magnetron is manufactured with the inner conductor of a coaxial line in place. This conductor is formed into

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a coupling loop inside the magnetron, and into an expanded voltage probe on the outside. The magnetron plugs into the side of a rectangular guide through a collar which forms the outer conductor of the coaxial. The length of the inner conductor is made an odd number of quarter-waves for the specific tube frequency.

(10) A tuning plunger in the end of the rectangular guide is adjusted for maximum transfer of energy. The guide conveys the energy to a cavity rotating joint at the antenna proper, where the mode of excitation is changed from $TE_{0,1}$ to $TM_{0,1}$. The conversion is accomplished by means of a large diameter tuning plug in the end of the cavity which rotates the electric field 90° in position to cause a radial electric field in the cavity. A standard form of rotating joint is used with a double choke to insure a good electrical short across the joint. This is necessary because of the very short wavelength.

(11) A second plug in the other end of the cavity couples it to the rectangular guide feeding the antenna. A metal plate is fastened along an equipotential line across the open end of the guide to support a dipole antenna. This metal plate has a second plate fastened to it at right angles, forming a reflector for the r-f energy. A dipole is placed a quarter-wave length in front of the reflector plate, and is excited both by the direct and reflected fields. It, in turn, radiates energy at the parabolic reflector, which is used to concentrate the energy into a narrow beam. The main advantage in this system is that the feed system enters from the back of the parabolic reflector, and therefore large metal masses in front of the antenna are avoided.

38. T-R SWITCHES.

a. General. (1) Whenever a single antenna is used for both transmitting and receiving, the problem arises of insuring that maximum use is made of the available energy. The simplest solution is to use a switch to transfer the antenna connection from the receiver to the transmitter for the duration of the transmitted pulse. As has been pointed out in section II, there are no practical mechanical switches available which can open and close in a few microseconds, or that can repeat the process at a rate comparable to the system PRF Electronic switches, or T-R switches, must therefore be used.

(2) In selecting a switch for this task, it must be remembered that protection of the receiver input circuit is equally as important as the power considerations. At frequencies where r-f amplifiers may be used, the amplifier tubes can be chosen to withstand large input powers without damage. At microwave frequencies the input circuit is the mixer, which is easily damaged by large applied signals, and so must be more carefully protected. This is particularly true of crystal mixers.

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(3) Generally speaking, if the receiver input circuit is properly protected the remaining receiver circuits can be prevented from blocking as the result of strong signals. A very strong main pulse signal still appears in the receiver output unless additional precautions are taken to eliminate it. This can be done by a receiver gate signal which turns on the receiver during only the desired time.

b. Open-wire T-R switch. (1) The T-R method proposed in paragraph 11c, can be used by substituting a simple spark gap for the double-pole switch (fig. 163). The spark gap makes a reasonably good switch because it is an open circuit until sufficient voltage is applied to cause the gap to arc over. The arc is formed by causing the gas or vapor between the electrodes to ionize. Once started,

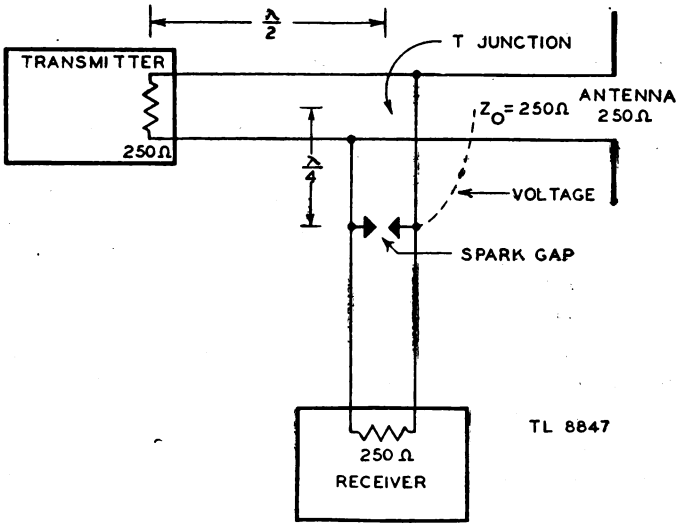

Figure 163. Open-wire T-R switch.

the running voltage across the gap is very low, and the resistance of the gap approaches a short circuit. The ionized gap voltage is independent of the applied power, so that the resistance varies with applied power. Air at atmospheric pressure requires about 30,000 volts per inch of gap to start the arc, while the running voltage is about 50 volts. The break-down and running voltages for inclosed gaps depend on the pressure and the gas or vapor used.

(2) For purposes of illustration it will be assumed that the characteristic impedance of the transmission line, the feed-point resistance of the antenna, the input impedance of the receiver, and the output impedance of the transmitter when generating r-f power, are all 250 ohms. The transmitter output impedance rises between pulses to 5,000 ohms. The resistance of the conducting gap is 50 ohms.

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(3) The pulse from the transmitter reaches the T-junction where it finds two paths to follow. Part of the pulse power goes down the receiver branch, and causes the spark gap to break down. As a result, a resistance of 50 ohms is placed across the 250-ohm line a quarter-wavelength from the T-junction. As seen from the T-junction the quarter-wave line terminated in 50 ohms appears as a much higher impedance of:

$$Z \text{ input} = \frac{250^2}{50} = 1{,}250 \text{ ohms.}$$

The pulse therefore has a choice of a 1,250-ohm path to the spark gap and a 250-ohm path to the antenna, since the antenna terminates the transmission line in its characteristic impedance. The pulse energy divides so that most of the energy takes the lower resistance path to the antenna, while the rest is used to keep the gap discharging. Because the receiver branch is a resonant line, there will be a voltage distribution across it as shown in figure 163. The voltage across the gap is lower than that across the T-junction, and is the voltage of the pulse reaching the receiver, since the rest of the receiver line is properly terminated by the receiver. If the gap resistance can be made lower, the magnitude of the pulse reaching the receiver will be reduced, and the T-R action improved. The lower gap resistance will also require less power from the T-junction.

(4) At the end of the transmitted pulse the gap is deionized, and signals which are picked up by the antenna reach the T-junction. Again there is a choice of two paths, one to the transmitter and the other to the receiver. The receiver path has an input impedance of 250 ohms since the spark gap is an open circuit and does not affect the receiver branch. The path to the transmitter is made a half-wavelength, and is terminated in 5,000 ohms. The half-wave section acts as a 1:1 transformer so that the T-junction sees 5,000 ohms. The received signals are divided, practically all of their energy taking the lower resistance path to the receiver. Note that if the output impedance of the transmitter decreases below 250-ohms instead of increasing while in the nonoscillating condition, the line from the transmitter to the T-junction is made an odd number of quarter-wavelengths to reflect a high resistance which effectively blocks the transmitter branch at the T-junction.

c. Anti-T-R switch. (1) The output impedance of the transmitter does not always change sufficiently to permit the use of a resonant line in blocking received signals from the transmitter. In such cases a second spark gap is used as an anti-transmit-receive switch to block the transmitter branch at the T-junction. Figure 164 shows the T-R system of figure 8 with an anti-T-R switch added. The T-R switch works in the same way as in the system just described.

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(2) The transmitted pulse passes down the line to the anti-T-R spark gap and causes it to arc over. The resulting short circuit is reflected back to the main feed line as a high impedance by the quarter-wave line. If the same values are used as in the previous example, the reflected impedance of the anti-T-R gap will be 1,250 ohms in parallel with the 250-ohm antenna line. During the transmitted pulse, then, the anti-T-R switch simply uses a small amount of the transmitted power.

(3) The anti-T-R gap is effectively an open circuit during the resting period. The shorting bar which is a quarter-wave below

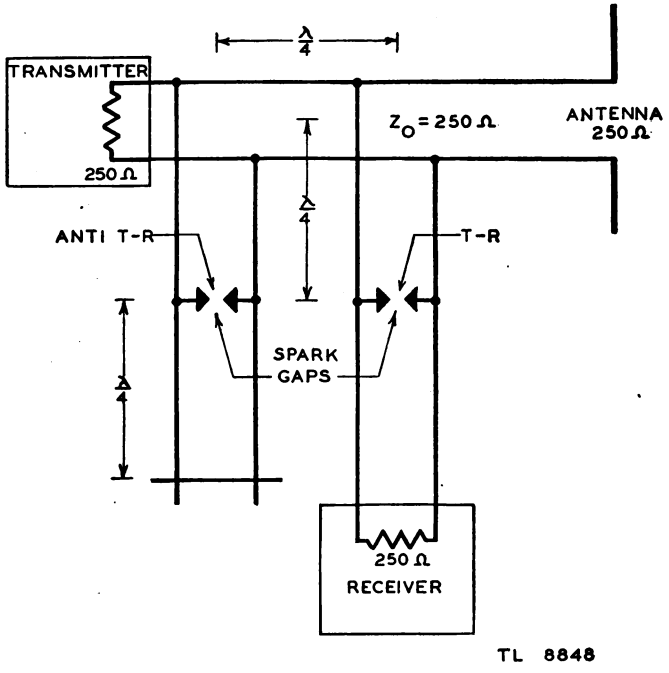

Figure 164. Anti-T-R switch.

the gap (fig. 164), is reflected by the half-wave anti-T-R line as a short circuit across the transmitter-feed line. This is reflected in turn to the T-junction as a high impedance by the quarter-wave section of the line, thus blocking this channel to received signals. Although the transmitter is in parallel with the anti-T-R branch, it will have no effect at this time, since it is placed across an apparent short circuit.

(4) Both the T-R and the anti-T-R switches require some of the transmitted-pulse power to operate them. This is undesirable, since part of their function is to increase efficiency. The amount of power required can be somewhat reduced, and the switching action im-

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proved, by using transformers to step up the voltage applied across the gap. Suppose that the signal is applied to the primary of a step-up transformer, and the spark gap is placed across the secondary (fig. 165). The secondary is tuned to obtain a very high secondary impedance when the gap is not conducting. This impedance is reflected to the primary as an open circuit.

(5) The voltage of the signal applied to the primary is stepped up in the secondary, which causes the spark gap to break down sooner than if the original signal were applied directly to the gap. The resistance of the conducting gap is placed across the tuned secondary, and is stepped down into the primary as a much lower resistance.

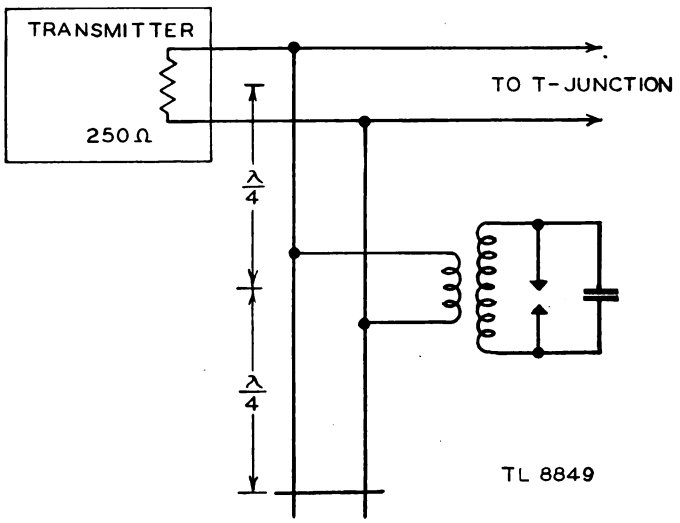

Figure 165. Anti-T-R switch with transformer.

Assuming a gap resistance of 50 ohms, and a step-down of 10:1, the primary will have an impedance of 5 ohms. The 5 ohms is reflected by the quarter-wave line as:

$$Z=\frac{250^2}{5}=12{,}500 \text{ ohms.}$$

The power taken by the gap will therefore be reduced by 10:1, as compared to placing the gap directly across the line.

(6) Transformers of the ordinary r-f type will not function well at the carrier frequencies used in radar, while the resonant line can be used as an excellent auto-transformer to produce the same results. Figure 166① shows an open wire line which uses a quarter-wave stub to step up the voltage applied to the anti-T-R spark gap and to step down its conducting resistance across the anti-T-R line.

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The stub can be considered as two sections of transmission line (fig. 166②), one of which is terminated in a short circuit, and the other in an open circuit. The shorted line is less than a quarter-wave long, which gives it an input impedance that is inductive. The open line, also less than a quarter-wavelength, is a capacitance. The two are in parallel, and since their total length is a quarter-wave, their reactances are equal, thus forming a parallel resonant circuit of very high impedance (fig. 166③). During the resting time, with the gap extinguished, the stub high impedance has very little effect in bridging the anti-T-R line.

(7) When energy is applied to the stub, a standing wave of voltage that is maximum across the gap is set up along its length. The received signals are normally not large enough to break down the gap. The transmitted pulse is large enough, however, and places a low resistance

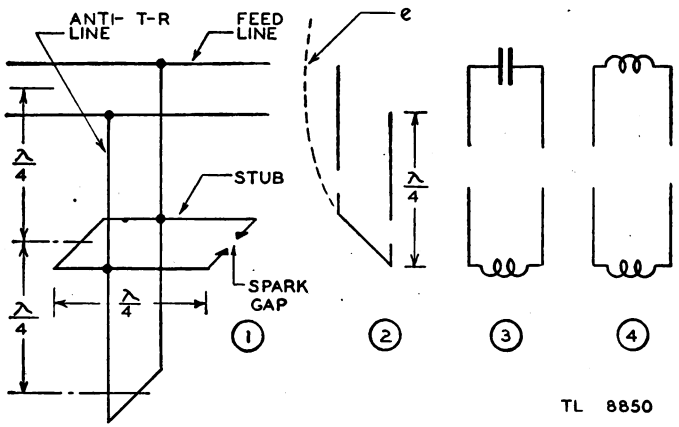

Figure 166. Resonant line transformer anti-T-R.

across the open end of the stub by causing the gap to conduct. The stub now consists of two lines in parallel across the anti-T-R line, each of which is inductive (fig. 166④). The result is to place a very low inductance across the anti-T-R line a quarter-wavelength from the feed line, reflecting the low impedance as a very high impedance to the feed line to limit the energy necessary to operate the gap.

d. Coaxial T-R switch. (1) The effectiveness of a T-R switch is dependent on the resistance of the spark gap as compared to the characteristic impedance of the transmission line system used. It was pointed out in the preceding discussion that resonant lines acting as transformers can be used to decrease the apparent gap resistance. When coaxial lines are used the resonant transformers must be used, since the impedance of a coaxial line is about 60 ohms as compared to the gap resistance of 30 to 50 ohms.

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(2) A simple form of coaxial T-R system is shown in figure 167. The magnetron is matched to the coaxial line during the transmitted pulse by the tuning stub. The length of the transmitter branch is adjusted so that the impedance seen at the T-junction looking back toward the magnetron is high when it is not generating r-f energy. The received signals therefore take the low impedance path to the receiver. The receiver-feed line is broken by the insertion of a 1:1 transformer in the form of a half-wave line shorted at both ends.

(3) The half-wave line is similar to a tuned circuit (fig. 168), and has an input impedance which is zero at the short circuit, increasing

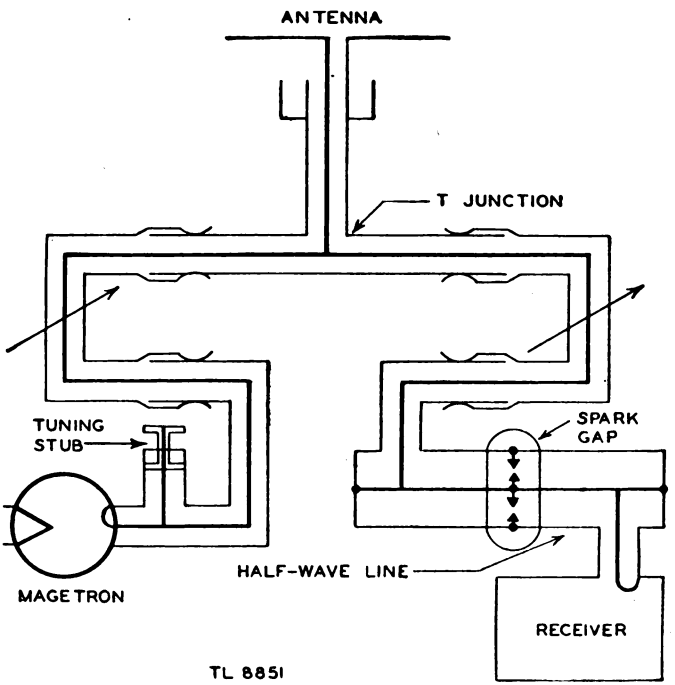

Figure 167. Coaxial T-R switch.

to a maximum in the center. The magnitude of the impedence depends on the Q of the half-wave line, and the connected load, in this case the receiver. The coaxial lines on either side of the half-wave line are connected to it at points which match the coaxial line characteristic impedance. The receiver input circuit terminates the feed line in its proper impedence, so that for received signals the receiver branch of the transmission-line system is matched throughout.

(4) The half-wave transformer has a spark gap placed between the inner and outer conductors at the middle of its length. The transmitted pulse passes from the T-junction down the receiver feed line, reaches the half-wave line, and causes a large voltage at the center

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which breaks down the gap. The gap resistance effectively short-circuits the center of the half-wave line, so that the input terminal of the half-wave transformer is connected to two short-circuited lines, each less than a quarter-wave long. The resulting impedances are inductive and in parallel, which presents a very low impedance to the receiver branch. The receiver feed line branch is adjusted in length to present the low impedance of the half-wave line as a high impedance at the T-junction. The voltage across the gap is stepped down by the half-wave line to a low value before being applied to the receiver. The use of the half-wave line therefore reduces the effective gap resistance, thereby lowering the power necessary to operate the T-R switch and reducing the transmitted signal applied to the receiver.

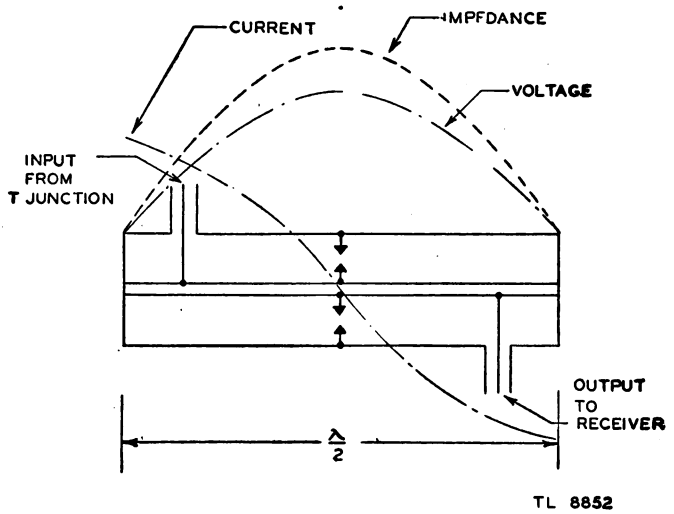

Figure 168. Half-wave line T-R switch.

(5) At microwave frequencies the transformer coaxial lines are reduced to such small dimensions that they became practically cavities, and are usually so constructed. The system discussed in section IV illustrates the use of a T-R switch built into a cavity for efficient switching action. The use of a cavity gives a higher Q for the transformer and thus improves the over-all operation.

e. T-R spark gaps. (1) The spark gap used in a given T-R system may vary from a simple one formed by two electrodes placed across the transmission line to one inclosed in an evacuated glass envelope with special features to improve operation. The requirements of the spark gap are that its resistance shall be very high until the arc is formed, and then be very low during conduction through the arc. At the end of the transmitted pulse the arc should be extinguished as rapidly as possible to remove the loss caused by the arc, and to permit signals from nearby targets to reach the receiver.

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(2) The simple gap formed in air has a resistance during conduction of from 30 to 50 ohms. This is usually too high for use with any but an open wire transmission line. The time required for the air surrounding the gap to be completely deionized after the pulse voltage has been removed is about 10 microseconds. During this time the gap acts as an increasing resistance across the transmission line to which it is connected. However, in a T-R system using an air gap the received signals reaching the receiver through the gap have half their proper magnitude after 3 microseconds. This is known as recovery time.

(3) The value of voltage to break down a gap, and the running voltage during the arc, can be lowered by reducing the pressure of the gas surrounding the electrodes. T-R tubes are therefore used in which the spark gap is inclosed in a glass envelope and the tube is

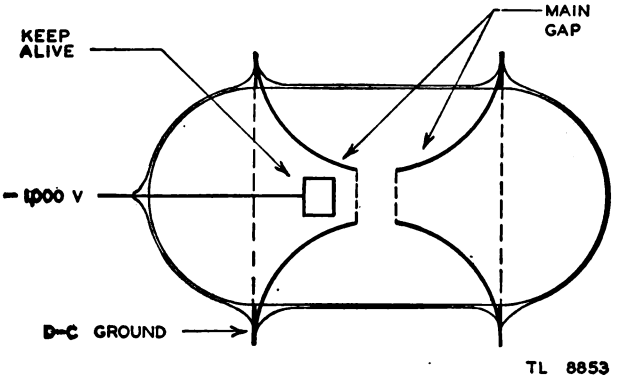

Figure 169. T-R tube with keep-alive.

partially evacuated. The arc is formed by conduction through an ionized gas or vapor so that the tube cannot be entirely evacuated; thus there is an optimum pressure which will give the best T-R operation. The recovery time or deionization of the gap can be reduced by introducing water vapor into the tube rather than air. A T-R tube containing water vapor at a pressure of 1 millimeter of mercury will recover in 0.5 microsecond.

(4) T-R tubes for use at microwave frequencies are built to fit into and be a part of the resonant cavity or transformer, as illustrated by the T-R box of section IV. The high Q of the cavity and the vapor in the evacuated portion of the tube reduce the power needed to maintain the gap and the power of the transmitted pulse which reaches the receiver. The speed with which this action takes place can be increased by placing a third electrode within one of the main electrodes of the gap (fig. 169). This electrode is known as a *keep-alive*, and has a potential of about −1,000 volts with respect to the main gap. A

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glow discharge is maintained by the keep-alive and one electrode of the main gap to provide ions for quickly forming an arc across the main gap when the transmitted pulse is applied. The negative voltage of the keep-alive also prevents stray ions from reaching the main gap to produce noises in the receiver.

(5) The life of the T-R tube is controlled by two main factors. The first and most common cause of failure is due to a gradual build-up of metal particles knocked loose from the electrodes of the gap and

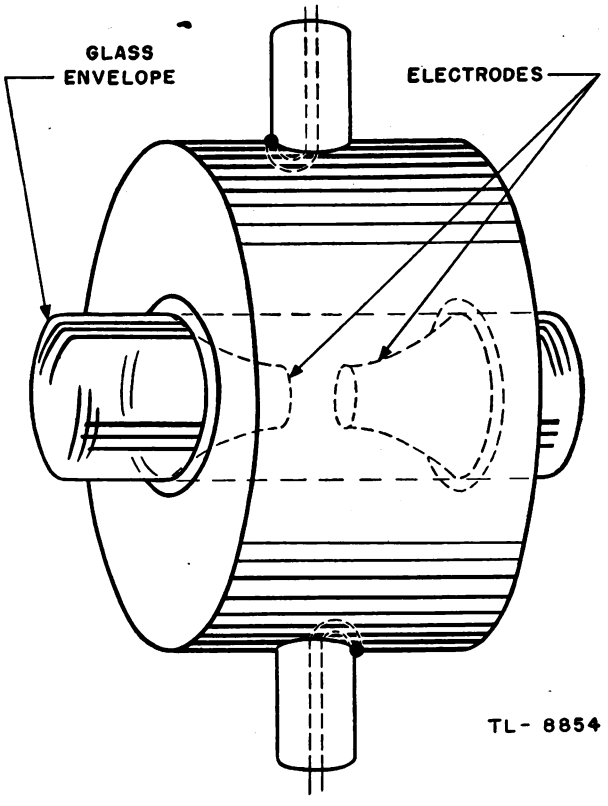

Figure 170. Cavity T-R box.

spattered on the inside of the glass envelope. These particles act as small, conducting areas which lower the Q of the resonant cavity and waste power. If the tube is continued in use for any length of time, the particles will begin to form a detuning wall within the cavity which will eventually prevent the T-R tube from functioning. The second cause of failure is due to an absorption of the gas within the tube by the metal electrodes. The result is to reduce the pressure gradually within the tube to the point where it becomes very difficult to break down the gap, and extremely strong signals are fed to the re-

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ceiver. Because both causes of failure are only gradually noticed, the T-R tube must be checked carefully and periodically for efficient operation.

f. Cavity T-R switch. (1) The majority of T-R tubes are mounted in cylindrical cavities, with the metal electrodes connected to and forming part of the end walls (fig. 170). The cavity is excited in a $TM_{0,1}$ mode in order to produce a strong electric field across the gap, and therefore be able to cause an arc with the minimum applied signal. The method of excitation used in the cavity of figure 170 is to terminate a coaxial feed line within the cavity by forming a coupling loop with the inner conductor. The coupling loop is a low impedance across the coaxial line so that current through the loop is large, and a strong magnetic field is set up. The loop is placed so as to reinforce the magnetic field within the cavity. The amount of coupling is controlled by rotating the loop on an axis formed by the inner conductor.

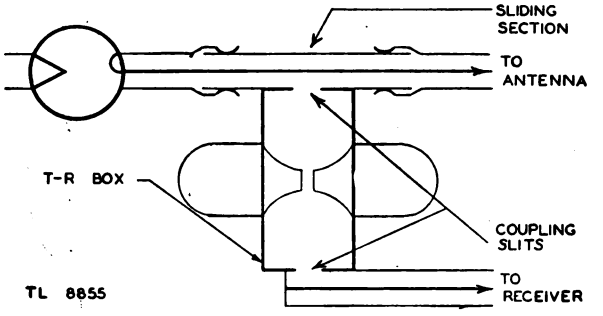

Figure 171. Slot-coupled cavity.

Signals for the receiver are removed from the cavity by a similar loop placed on the opposite side of the gap from the input loop. This is the coupling method used by the T-R box of section IV.

(2) A second method of feeding the cavity from a coaxial line is to use slots which couple the field of the line to that of the cavity (fig. 171). The output of the magnetron is matched into a coaxial line which feeds the transmitted pulse to the antenna. Near the magnetron the outer conductor of the coaxial line is made into a sliding section having a side aperture or slot in the center. The slot opens into the resonant cavity of the T-R box on the periphery. Another slot on the opposite side of the cavity is cut through into the receiver coaxial line, which is shorted at the edge of the slot.

(3) During the transmitted pulse, energy is coupled into the cavity and produces a large voltage across the gap. The gap breaks down, forming an arc which short-circuits the center of the cavity. The field built up within the cavity is very weak because of the detuning of the cavity during the arc, and has the effect of a short circuit across

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the transmitter feed-line slot. Because the field is weak, very little energy is coupled into the receiver feed line.

(4) At the end of the transmitted pulse the magnetron impedance changes, so that received signals see a mismatch at the magnetron and are reflected. The position of the slot into the cavity is adjusted by means of the sliding joint to be placed at a current maximum of the coaxial line (fig. 172). The large current produces a strong magnetic field which leaks through the slot into the cavity to reinforce the field of the cavity. The received signals are not strong enough to break down the gap, and the field within the cavity is not affected by the presence of the gap. The slot into the receiver feed line permits some of the field of the cavity to link the inner conductor of the line at a point which is a current maximum. By selecting the proper size and shape of the slots, the received signals are passed with very little loss to the receiver. The position of the antenna feed-line slot can be

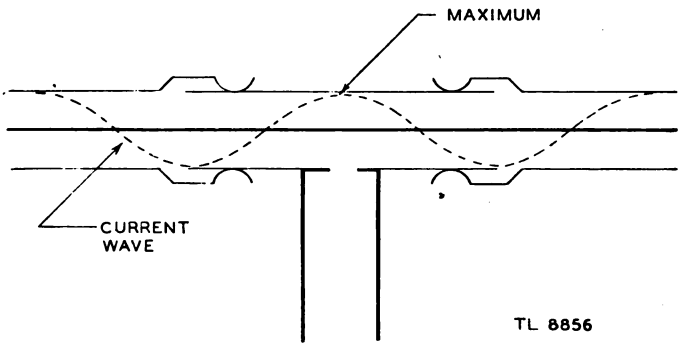

Figure 172. Current wave reflected by magnetron.

adjusted to absorb all of the received line energy from the antenna feed line, and therefore to prevent standing waves between the T-R switch and the antenna.

g. Waveguide T-R switch. (1) Resonant cavity T-R switches are applied to waveguides both directly or indirectly to obtain switching action. The indirect method uses a coaxial line T-R system, and then couples the coaxial line into the waveguide which feeds the antenna. When large losses might be incurred by the use of coaxial line, the resonant cavity can be coupled directly to the waveguide. Figure 173 shows a direct method of cavity T-R switching in a waveguide feed system. The waveguide terminates in the antenna on one end and a shorting plate at the other. The magnetron uses a voltage probe to excite the waveguide. The transmitted pulse travels up the guide, spilling into the cavity through a slot. The cavity builds up a strong electric field across the gap, breaking it down, and detuning the cavity. The impedance seen at the slot by the guide is

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decreased to an approximate short circuit which effectively seals the opening and passes the pulse energy to the antenna.

(2) The signals received during the resting time travel down the guide to the magnetron and the shorting end plate, where they are

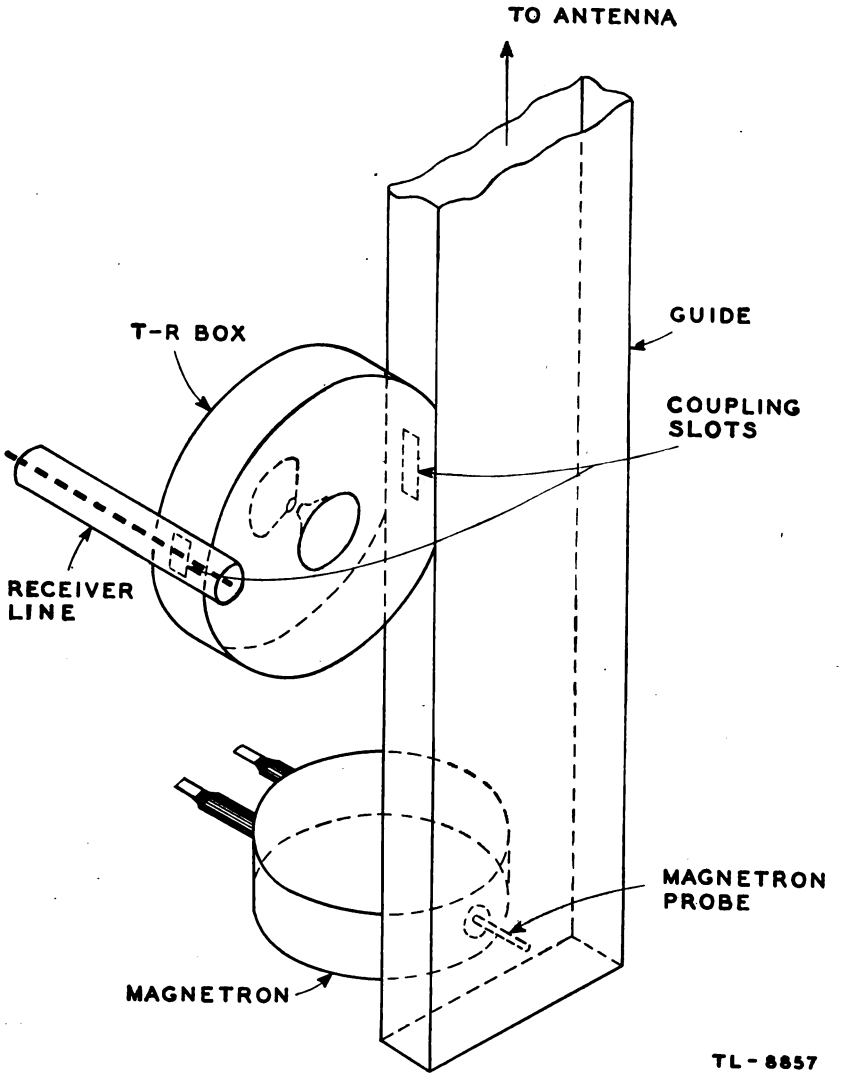

Figure 173. Waveguide using cavity T-R box.

reflected. The slot into the cavity is placed so that it is located at a maximum of the standing wave magnetic field produced by reflections. The maximum field therefore links the magnetic field of the cavity. The received signals are not strong enough to cause an arc so that the

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cavity field is undisturbed by the gap, and couples into the receiver coaxial line to give maximum energy transfer.

(3) The cavity T-R switch can also be applied to branch lines of the waveguide (fig. 174). The magnetron is coupled to the guide by a voltage probe to produce proper excitation. In order to insure maximum use of the received signals an anti-T-R switch has been included. The transmitted pulse travels from the magnetron to the anti-T-R branch where part of the energy turns in to the gap. A slot is placed across the waveguide a half-wavelength from the main

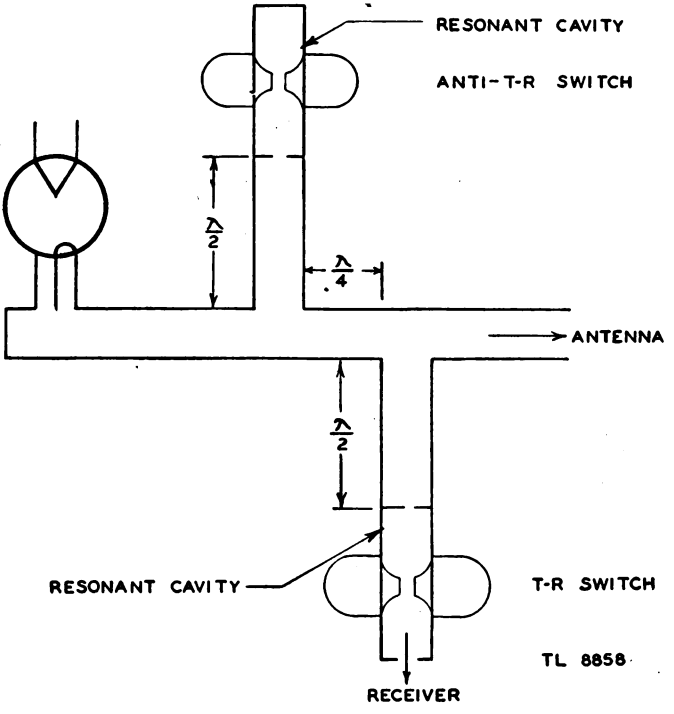

Figure 174. Cavity T-R box applied to branch lines of waveguide.

guide, and passes the r-f energy through into the cavity. The cavity builds up the electric field, breaks down the gap, and as a result produces a short circuit across the coupling slot. The short circuit of the slot is reflected back to the main guide a half-wave away to close the mouth of the anti-T-R branch.

(4) Most of the energy is therefore directed down the guide to the antenna. On reaching the receiver branch the same effect is produced by the T-R switch a half-wavelength from the main guide. Since both openings are effectively closed by the gaps, maximum energy is transferred between the magnetron and the antenna.

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(5) During the resting time, the anti-T-R spark gap is not broken down by the received signals, so that the input to the cavity is practically an open circuit. This is reflected to the main guide as an open circuit. The received signals are in effect turned back by the apparent open circuit at the mouth of the anti-T-R branch setting up reflections which a quarter-wave away at the T-R branch produce a short or closing of the main guide. The signals are directed into the T-R branch where they pass through the resonant cavity to the receiver.

(6) Instead of using resonant cavities and T-R tubes, the branch waveguides can use resonant slots which also act as spark gaps (fig. 175). The resonant slot is a partition across the guide with an aper-

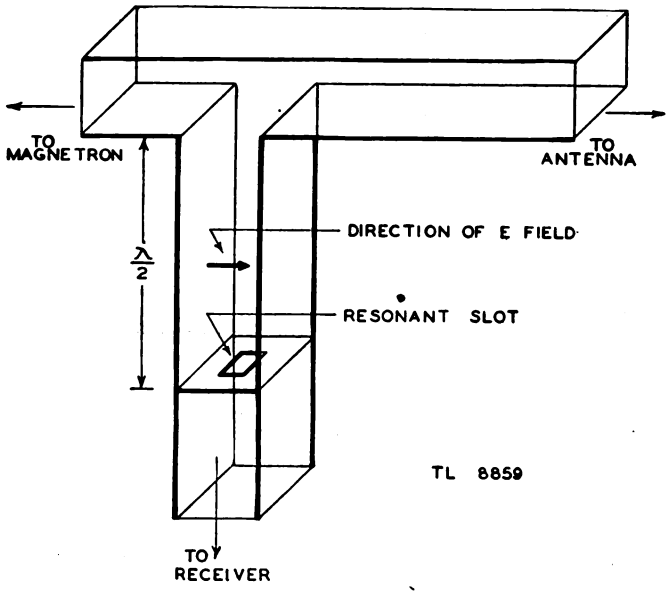

Figure 175. Slot type T-R switch.

ture whose dimensions make it look like a parallel resonant circuit at the carrier frequency. The dimension in the direction of the electric field is made small so that the transmitted pulse will cause an arc. The arc closes the conducting surface of the slot, providing a short circuit which is reflected by the half-wave line to the main guide.

39. LOBE SWITCHING.

a. Dual antennas. (1) The accuracy of angular measurement depends on the sensitivity of the antenna to a change in the direction of the arrival of the echo signals. In paragraph 5 the idea is discussed of using two patterns the axes of which are displaced from each other sufficiently to cause the patterns to cross over at less than

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the 85 percent maximum signal point. The advantage which is obtained is that of comparing two signals whose changes in magnitude are great per degree change in azimuth, and whose directions of change are opposite. The operator is better able to select the correct on-target position of the antenna since he sets to a position which makes the two signals equal for the target being tracked.

(2) An antenna system which uses the double-lobe principle must include provisions for obtaining the two patterns displaced from each other, and some method for comparing the received signals from both lobes on the indicator. The simplest system is to use separate antennas, receivers, and a common indicator. It is more economical, however, to use a single receiver which can be switched between the lobes. Figure 176 shows the components of an elementary lobe-switching system.

(3) Separate antennas are mounted so that their patterns overlap, intersecting at approximately the half-power points. The feed line from the two antennas are brought to a double-pole double-throw switch. The switch alternately selects the signals from antenna 1 and then from antenna 2 to be amplified by the receiver. The output of the receiver is therefore a combination of the two groups of signals from the two antennas. These signals are separated by a single-pole double-throw switch so that they may be compared on the indicator. The two switches are thrown in synchronism by a switch motor.

(4) The sequence of events in the lobe-switching operation is shown in figure 177. The echo signal from the target (fig. 176) induces a smaller voltage in antenna 1 than antenna 2. It is assumed that system PRF is four times the switching frequency, so that two pulses are received while the receiver is connected to antenna 1, and two while the receiver is connected to antenna 2. Starting from the instant that the switch moves to the antenna 1 position, the receiver amplifies two cycles of echo signals from antenna 1, and then switches to antenna 2 for two cycles. Thus the output of the receiver is a series of pulses that are alternately proportional to signals received by antenna 1 and then to signals received by antenna 2. The indicator output switch separates the pulses by placing those from antenna 1 on the left deflecting plate, and those from antenna 2 on the right deflecting plate.

(5) During the time that signals from antenna 1 are being applied to the indicator, the right deflecting plate is effectively grounded, and the trace produced is shown by figure 178①. When the switch is moved to antenna 2, the left deflecting plate is grounded, and the indication is as in ②. The indicator cathode-ray-tube screen has sufficient persistence so that when the switch motor runs at normal speed, the two traces appear simultaneously as in ③. The operator

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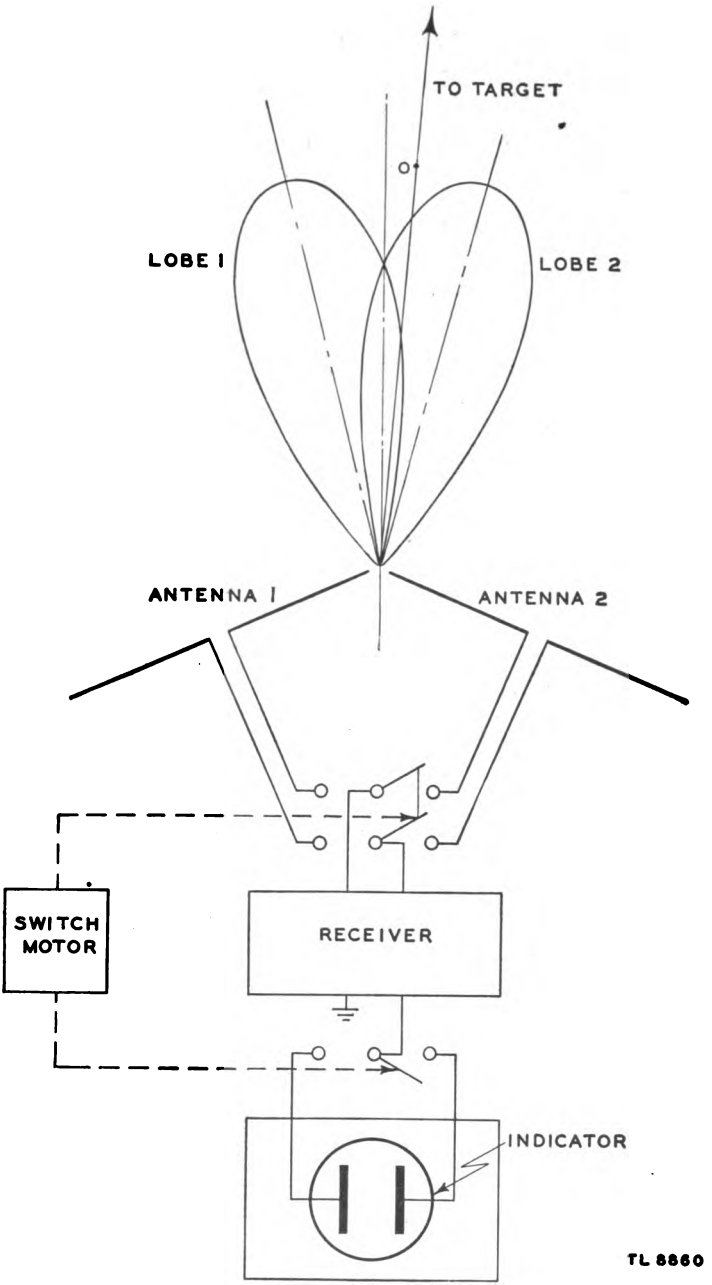

Figure 176. Mechanical lobe switch.

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the 85 percent maximum signal point. The advantage which is obtained is that of comparing two signals whose changes in magnitude are great per degree change in azimuth, and whose directions of change are opposite. The operator is better able to select the correct on-target position of the antenna since he sets to a position which makes the two signals equal for the target being tracked.

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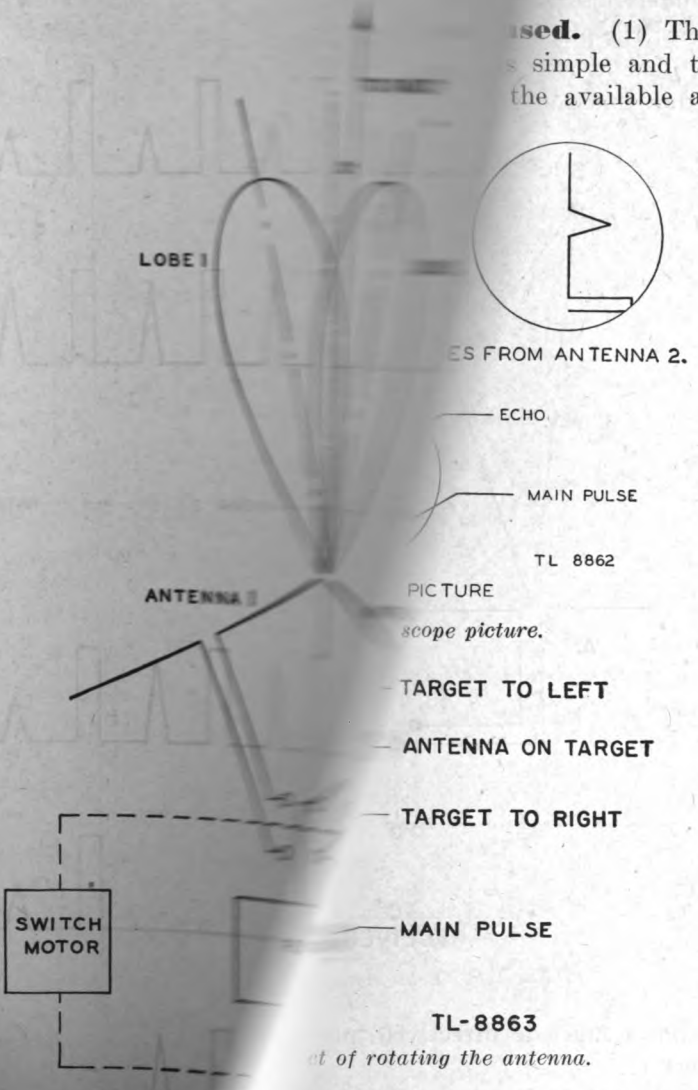

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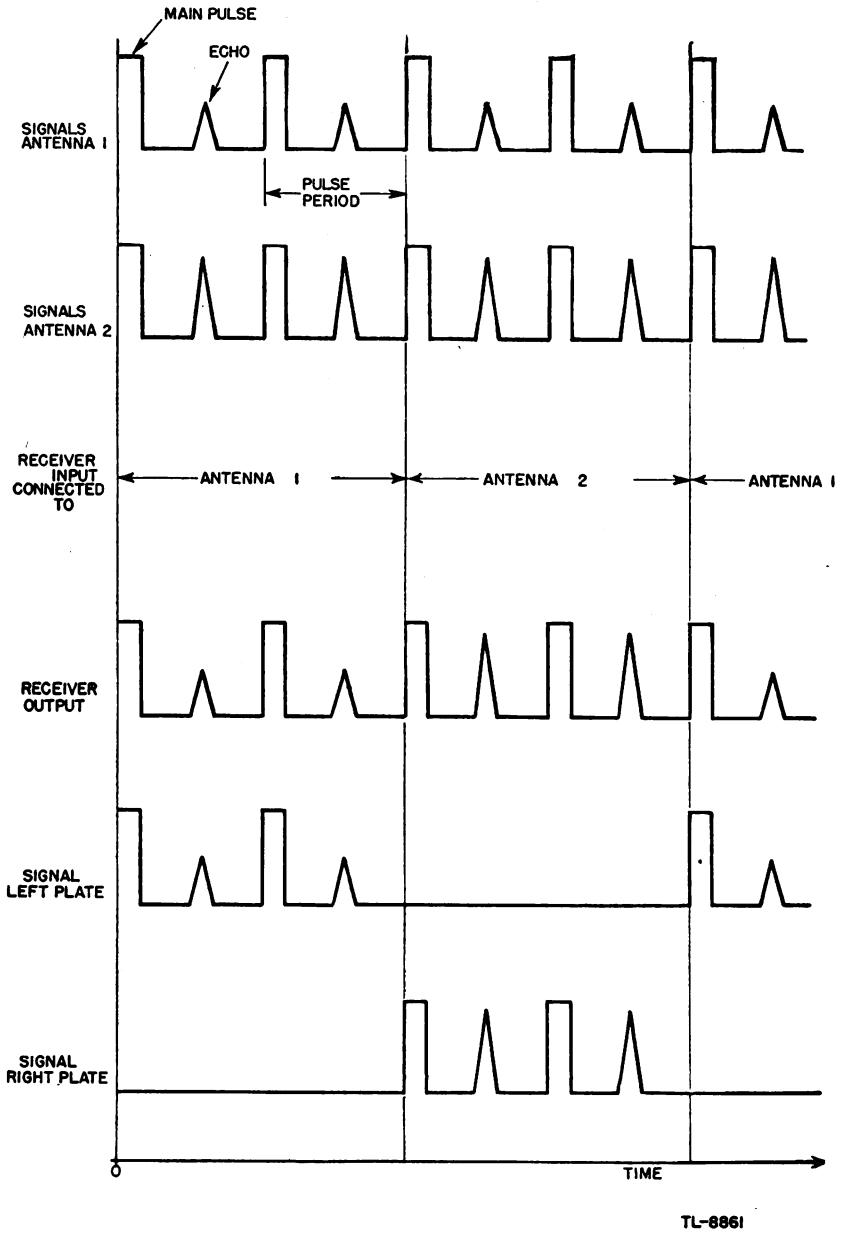

Figure 177. Lobe-switching waveforms.

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adjusts the position of his antenna in azimuth until the pulses representing the target to be tracked cause equal deflection to right and left (fig. 179).

b. Single antenna, externally phased. (1) The two-antenna method of obtaining double lobes is simple and trouble-free, but is inefficient because only half of the available antenna

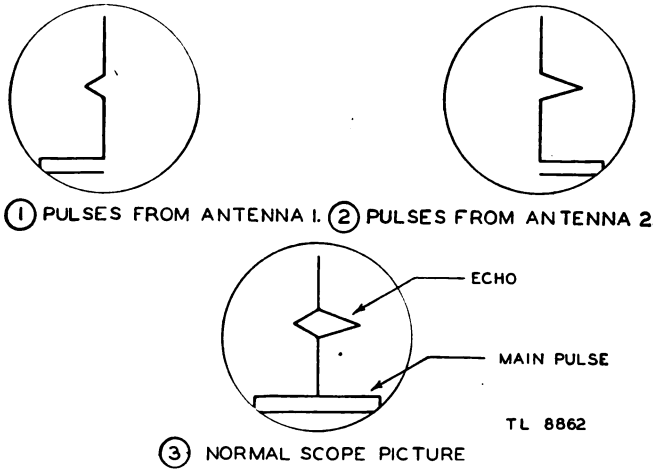

Figure 178. Normal scope picture.

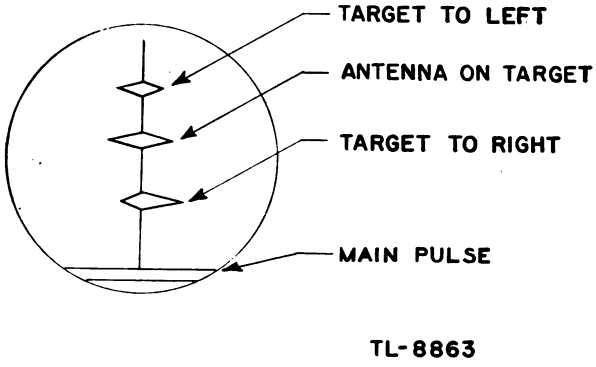

Figure 179. Effect of rotating the antenna.

space is used to receive echo signals at a time. The complete antenna can be used for receiving all signals by phasing one half of the antenna against the other half to produce a pattern whose axis is shifted first to the right and then to the left.

(2) In figure 180, an antenna four dipoles wide is used to receive echo signals from targets, and to measure their azimuth. The antenna is divided into a left half A, and a right half, B, connected by an external phasing section and feed line. A signal reflected

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from a target at ① travels the same distance to reach A as it does to reach B. The r-f voltages induced in A are therefore in phase with those induced in B. The voltages of A and B travel toward each other over the phasing section, meeting and combining at the middle of the phasing section where the receiver feed line is connected. Since this junction is equidistant from A and B, the voltages are

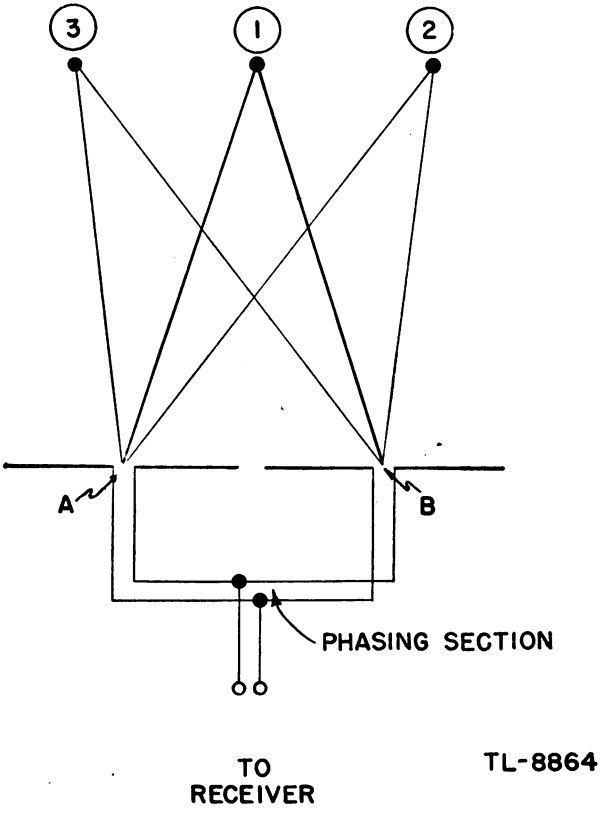

Figure 180. Echo signal paths to antenna.

still in phase and add directly to produce the voltage which reaches the receiver.

(3) If the target moves to ②, the echo signal reaches B first, and then travels on to A. The alternating voltages induced at A therefore lag behind those induced at B, and the instant of maximum voltage at A occurs after the maximum voltage at B. This is due to the greater distance between ② and A as compared to that between ② and B. The induced voltages travel over equal-length paths to reach the receiver feed line, so that their phase relationship remains the same as at the dipoles. The effective voltage which reaches the receiver from

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the target at ② is less than that from the target at ① because of this phase difference (fig. 181).

(4) If the target is moved to ③ (fig. 180) the voltage induced at A leads that induced at B, and the voltage reaching the receiver is less than that produced by the target at ①. With the receiver feed

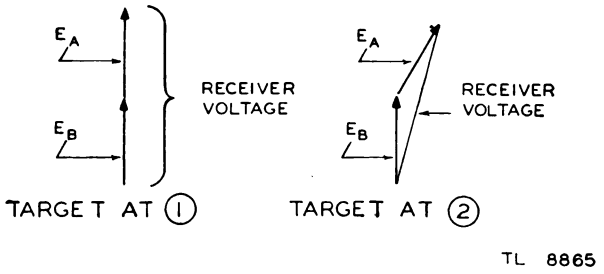

Figure 181. Phase addition of received signals.

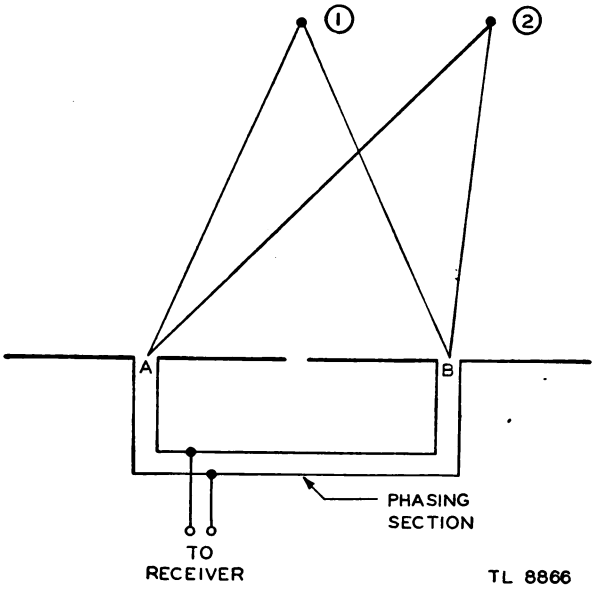

Figure 182. Off-center feed to receiver.

line connected to the center of the phasing section the target returns maximum signal only from ①.

(5) The difference in phase between the voltages from A and B can be controlled by varying the distance that each voltage travels in reaching the receiver feed line. In figure 182, the target is located at ② (fig. 180) and the receiver feed line is connected to the left of the center of the phasing section, so that the voltage from B travels further over the phasing section than the voltage from A. The addi-

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tional path of travel for the voltage from B is made electrically equal to the additional path traveled in space by the echo signal in reaching A. The two voltages at the receiver feed line are therefore in phase, and add directly.

(6) If the feed-line connection is fixed, and the target is moved to ①, the voltages induced in the dipoles are in phase. When these voltages reach the receiver feed line, however, that from B lags that from A, and the signal which reaches the receiver is not maximum. Maximum receiver input voltage is produced only when the target is at ② when the receiver feed line is connected as shown.

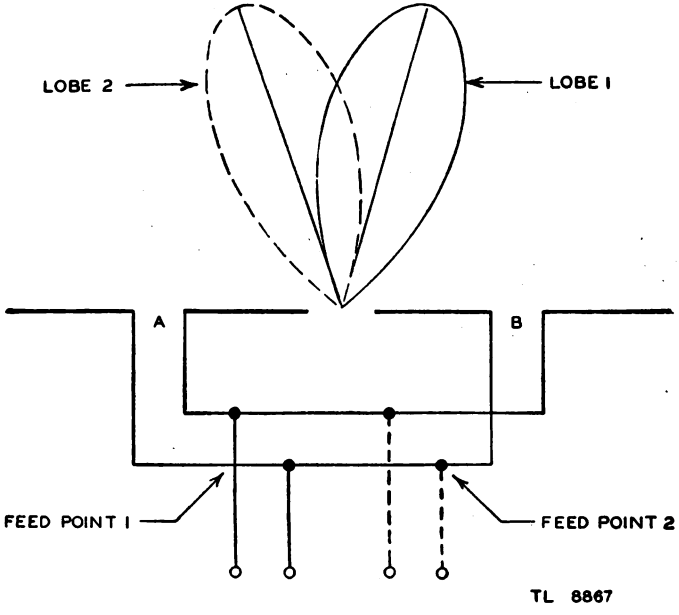

Figure 183. External phasing to produce double lobes.

(7) A field pattern of the antenna system with a phase delay introduced in the feed line to the right half, B, is shown in figure 183. The distance from feed point ① to B is less than a half-wavelength more than the distance to A. The phase delay thus introduced bends the pattern to the position of lobe ①. If the feed line is connected to feed point ② to produce the same phase delay in the path to A, a mirror image of lobe ① is obtained as shown by lobe ②. By alternating the point of connection a double lobe system is available for accurate azimuth measurement which uses the entire antenna for receiving each echo signal. The gain realized approaches twice that of a half section, and the beam width is reduced for more accurate bearings.

(8) The amount of phase delay introduced controls the positions of the double lobes. When the delay path-difference is greater than a

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half-wavelength, the lobes are bent toward the feed point, rather than away, as in the example given.

(9) The problem of shifting the feed-point connection from one side of the antenna to the other is a difficult one to solve mechanically. The phase delay can be introduced electrically by placing a reactance across one of the branch feed lines. Figure 184 shows an antenna fed by a coaxial line which branches symmetrically to each half of the array. A half-wave line is placed across each branch line to act as a 1:1 transformer. The inner conductor of each line is terminated by

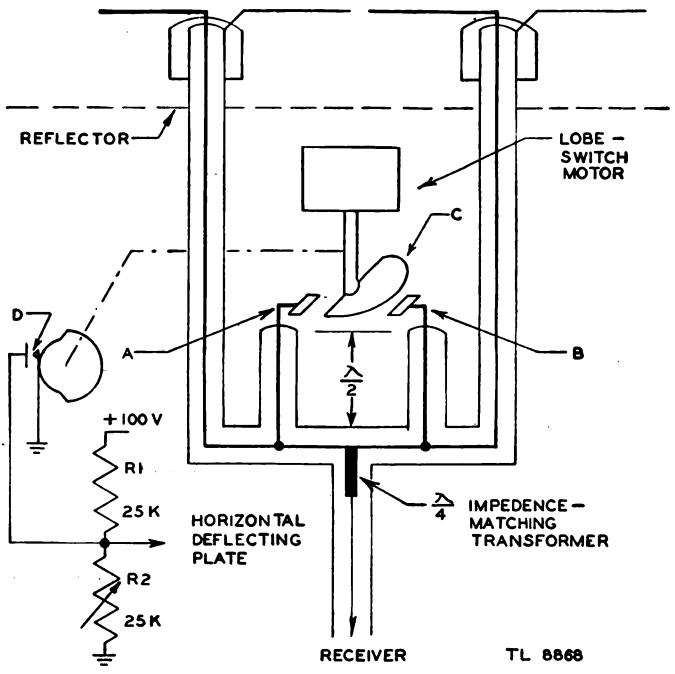

Figure 184. Reactance-phased double-lobe antenna.

a small plate of a capacitor, *A* and *B*. The other plate, *C*, is a half disk which is rotated by the lobe switch motor so as to engage each small plate for approximately one-half of a revolution.

(10) With disk *C* in the position shown, plate *A* is isolated and presents an open circuit across the left coaxial line. The open circuit is reflected down to the left branch line, and has no effect. The spacing between *B* and *C*, however, is such as to form a small capacitor which terminates the right coaxial line. This capacitance is reflected to the right branch, and is shunted across the line to increase the effective electrical length of the line. The result is to introduce a lag in the echo signals received by the right half of the antenna. As the lobe switch motor rotates the lag is placed alternately on the right

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and left branches, and therefore causes the pattern of the antenna to shift from right to left.

(11) The signals are separated on the indicator screen by means of a variable position voltage controlled by a cam-operated switch. The cam is rotated by the lobe switch motor at the same rate as the capacitor disk *C*. The cam is shaped to close switch *D* during the time the lobe is bent to the left, and to leave the switch open while the lobe is bent to the right. Switch *D* shorts resistor R_2 when closed so that the positioning voltage to the indicator is zero. Resistor R_2 determines the voltage to the indicator when *D* is open.

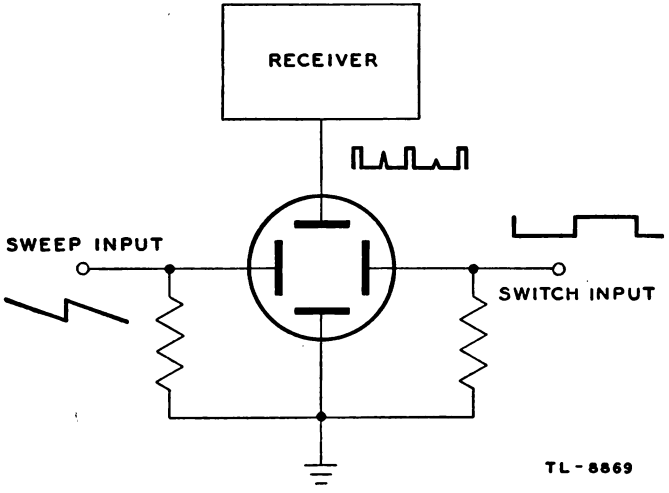

Figure 185. Indicator connections for echo separation.

(12) The output of the receiver consists of pulses from both lobes of the antenna array. These pulses are applied directly to the vertical deflecting plates of the indicator. The horizontal deflecting plates receive a saw-tooth sweep voltage synchronized to the PRF of the system, and the positioning voltage from switch *D* (fig. 185). With disk *C* near plate *B* (fig. 184), the lobe is bent to the right, and switch *D* is open. The positioning voltage is positive and causes the sweep trace to appear to the right of the center of the indicator to the left, and switch *D* is closed, shorting resistor R_2. The positioning voltage is zero, and the sweep trace appears to the left of the center line (fig. 186①). As the lobe switch motor rotates, the lobe and sweep trace are moved instantly from right to left, and left to right, building up a normal scope picture (fig. 186③). The amount of separation, or spread, between echo pips is controlled by resistor R_2, which can be adjusted to from 0 to +50 volts as the positioning voltage when switch *D* is open.

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e. Single antenna, internally phased. (1) The antenna system just described provides either the left or the right lobe for receiving echo signals, depending on the position of the lobe-switching motor. Another choice of antenna system is available which produces both lobes simultaneously, and which uses electronic switching. The main advantage is to eliminate the switch contacts, and the noise resulting from dirt and incorrect adjustment of the contacts. The phasing is accomplished by an adjustable length line which connects the inner dipoles (fig. 187). A separate feed line is connected to each

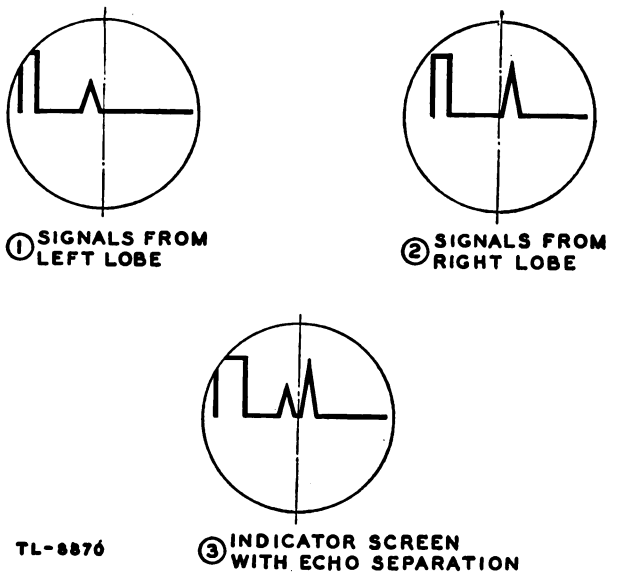

Figure 186. Echo separation on indicator screen.

half of the antenna. Each feed line runs to a separate input to the receiver.

(2) Echo signals arriving at the antenna array induce voltages which appear at A and B. The total voltage which reaches the receiver over feed line A is a combination of the voltage induced on A and that induced on B which travels over the phasing section to A. The phase of the voltage from B with respect to that at A depends on the path length from B to A, including the phasing section. The relative phase can therefore be controlled by varying the length of the phasing section.

(3) An echo signal received from a direction perpendicular to the face of the antenna induces in-phase voltages at A and B. This means that the induced voltage on the right feed point at A and the left feed point at B should be 180° out of phase. If the phasing section is of zero length the induced voltage at B travels one wave-

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length to reach A out of phase with the induced voltage at A, giving cancelation. Resetting the phasing section to have an over-all length of a half-wave produces a 1½-wavelength path, and the voltage from B arrives in phase with that of A to give a maximum. Setting the phasing section to add a length to the path from A to B which is other than an odd multiple of a half-wave makes the phase difference between the voltages such as to produce maximum signal at some direction other than straight ahead.

(4) Suppose that the echo signal is coming from a direction to the right of the perpendicular to the antenna (fig. 188). The signal induces a voltage at A which lags the voltage induced at B. By adjusting the phasing section to the correct length the voltage at B

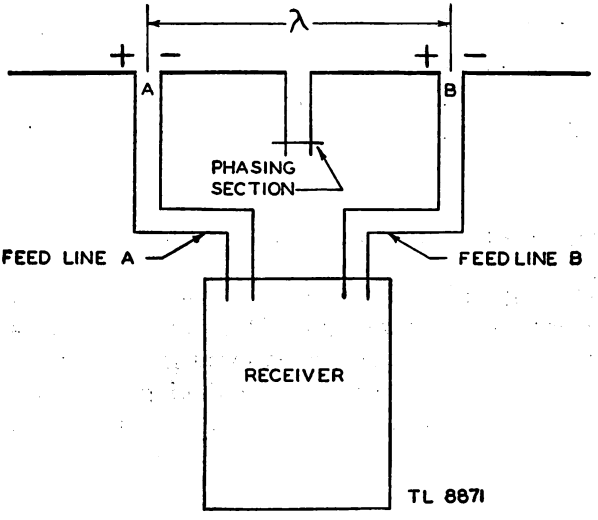

Figure 187. Internally phased double-lobe antenna.

can be delayed in reaching A to reduce the phase difference to zero. The two voltages at A will add in phase to produce a maximum. The voltage induced at A travels to B to produce a second available voltage for the receiver. The voltage from A, already lagging, receives an additional delay while traveling to B, so that the total voltage at B is not a maximum. In order to cause the receiver voltage at B to be a maximum, the target moves position to the left of the perpendicular. The second position of the target is at angle to the left of the perpendicular which is equal to the angle of the first position to the right.

(5) The use of the interval phasing section produces two lobes which are symmetrical about the perpendicular to the array. If the total length of path from A to B is between 1 and 1½ wavelengths, the lobe is bent away from the side of the antenna to which the feed line

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is attached. If the length of path is between 1½ and 2 wavelengths, the lobe is bent toward the side to which the feed line is attached.

(6) In order to make use of the two lobes whose signals reach the receiver over separate feed lines, the receiver has two input channels and an electronic switch to select them alternately. The output of these channels is combined and applied to a conventional superhetero-

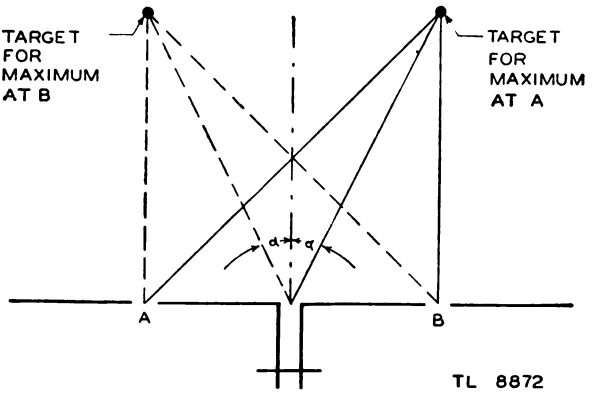

Figure 188. Adjusting phasing section for double lobes.

dyne receiver (fig. 189). The electronic switch produces two 1,000-cycle-per-second square-wave signals that are inverted with respect to each other. The signals are applied to the grids of the r-f amplifiers as blocking voltages. Since they are out of phase, r-f amplifier *A* conducts and amplifies while *B* is nonconducting. Every half cycle of the switching voltage this condition is reversed. Thus the signal

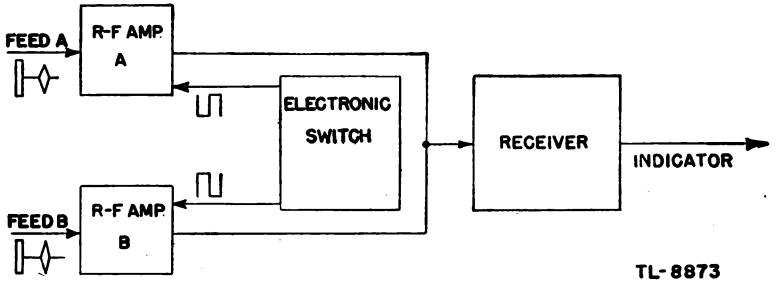

Figure 189. Block diagram of receiver with electronic switch.

applied to the single channel amplifier which comprises the rest of the receiver is alternately a signal from feed line *A* and than a signal from feed line *B*.

(7) Figure 190 shows the circuit diagram of a typical electronic switching system. Tubes V101 and V102 are duplicate r-f amplifiers for the signals appearing on feed lines *A* and *B* of figure 187. Trans-

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former coupling is used for the input circuits to maintain a balanced feed-line system. The plate load circuit is common to both tubes, so that their outputs are combined as the input to the second r-f amplifier of the receiver. The grid of tube V101 is returned to ground through

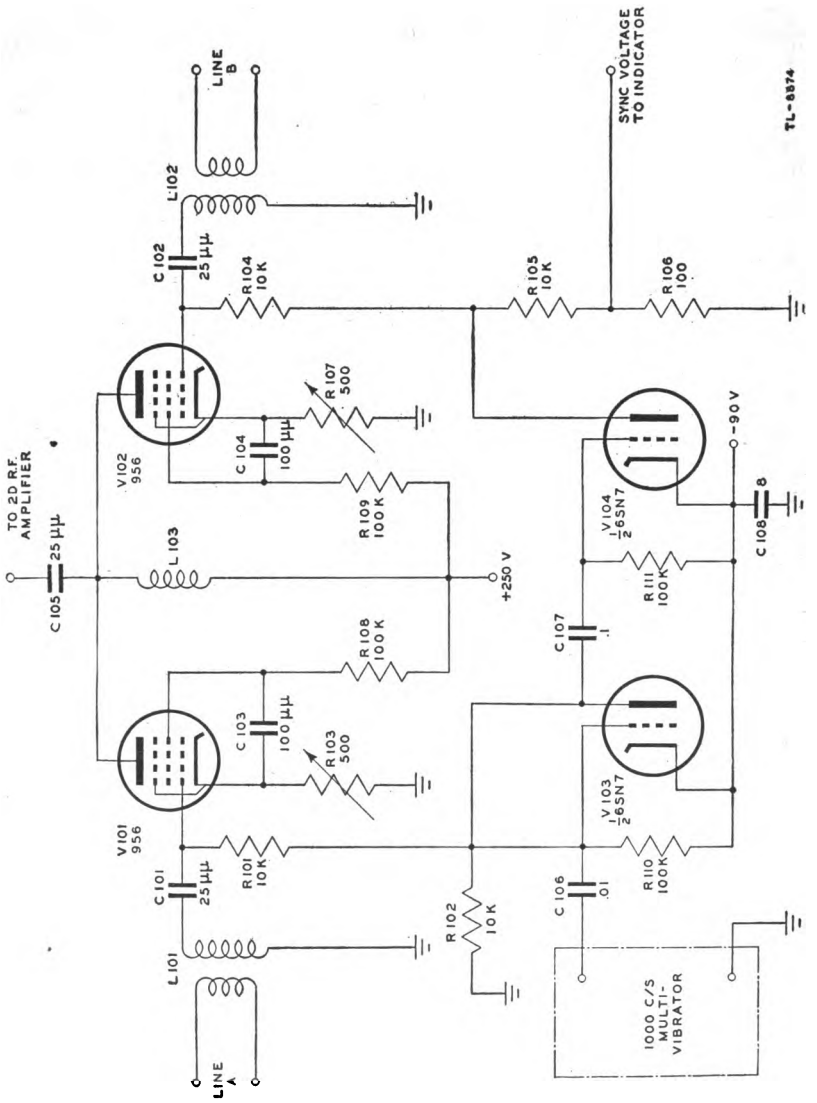

Figure 190. Circuit diagram of electronic switch.

resistors R101 and R102, the plate load of V103, the first switch amplifier. Similarly, the grid of V102 is returned to ground through resistor R104 and plate load of the second switch amplifier.

(8) The output of the 1,000 cycle-per-second multivibrator is an approximate square-wave of sufficient amplitude to overdrive tube

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V103. This tube and V104 form a two-stage amplifier to further square the output of the multivibrator. The plate potential is caused to vary between ground and a negative value by applying a negative plate supply in the cathode instead of a positive one in the plate. Thus, when the output of the multivibrator swings to a positive maximum, tube V103 conducts, and the electrons flow from the plate to ground through resistor R102. This causes the plate to be negative with respect to ground. The negative voltage change across the plate load is coupled to V104, and cuts this tube off. Since there is no electron flow, there will be no voltage drop across R105 and R106, and the plate of V104 is at ground potential. As the output of the multivibrator swings negative, V103 is cut off, and its plate rises to ground potential, and a positive change is passed on to V104. V104 conducts and its plate voltage becomes very negative. Therefore, when the plate of V103 is at ground potential the plate of V104 is negative, and when the plate of V103 is negative, V104 is at ground.

(9) The grids of the r-f amplifiers are directly coupled to the plates of the switch amplifiers, so that the plate potential of V103 is a bias for V101, and that of V104 is a bias for V102. V101 operates as an amplifier with cathode bias when V103 is cut off, and is cut off when V103 conducts. V102 operates in the same manner with V104. Since V104 inverts the signal from V103, V101 and V102 alternate in operation. The signal developed across the common load inductor L103 is alternately the signal from feed line *A* and then from feed line *B*.

(10) The gains and plate currents of the two r-f amplifiers must be equal in order for the switching system to work correctly. Otherwise, the indicated equal signal position of the antenna will not correspond to the correct on-target position, and a square-wave modulation will appear in the output. This is taken care of by balancing the gains of the tubes, V101 and V102, with the individual gain controls, resistors R103 and R107. The indicator is similar to that described in the previous paragraph, and requires a square wave to mix with the sweep voltage for spreading the echo pips. This signal must be synchronized to the switching action, and is obtained by taking the voltage drop across resistor R106 in the plate circuit of V104. The receiver output is applied to the vertical deflecting plates of the indicator.

40. CONICAL SCANNING.

a. General. (1) The principle of lobe switching can be extended to give accurate azimuth and elevation simultaneously when applied to antenna systems using parabaloidal reflectors. The name given to this type of operation is conical scanning because an off-center lobe is produced which is rotated about the axis of the reflector

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(fig. 191). The lobe axis describes a cone in space around the axis of the reflector.

(2) The echo signal received from a target which lies on the axis of the reflector has the same amplitude for all positions of the lobe. If the target moves away from the reflector axis the signal received varies approximately sinusoidally with the rotation of the lobe. As the axis of the lobe nears the target the signal increases, and as the axis of the lobe moves away the signal decreases. The relative phase of the signal variation therefore indicates the direction of the target from the reflector axis. The magnitude of the signal variation indicates the distance away from the reflector axis to the target.

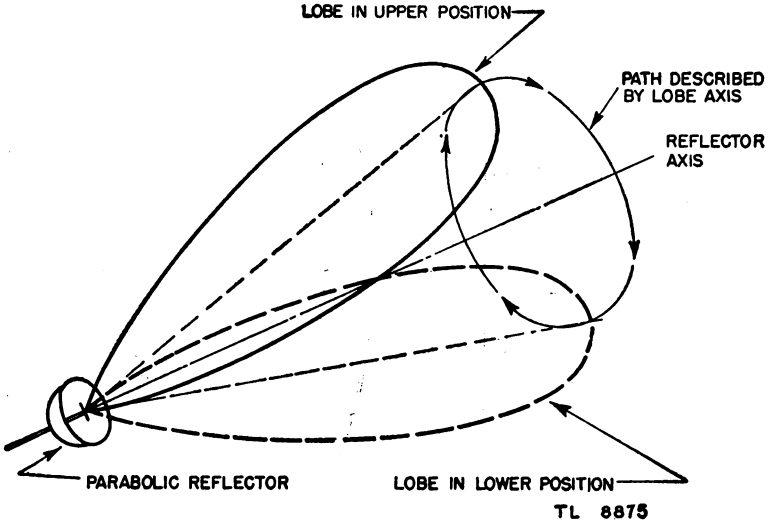

Figure 191. Conical scanning.

(3) Conical scanning is applied to microwave systems which are used for fire control against aircraft. The circuits which supply the indicator can be used simply to indicate the relative position of the target, or they can be made to track the target automatically as well as indicate its position. The discussion here will be confined to the methods for producing the conical scan.

b. Off-center dipole. (1) The simplest method to produce conical scanning is to use a coaxial line terminated in a dipole. The coaxial line is bent sufficiently to displace the electrical center of the dipole slightly away from the focal point of the reflector (fig. 192). The coaxial line and dipole are rotated by a scanning motor at a speed of 20 to 60 revolutions per minute.

(2) The apparent source of energy for the parabaloidal reflector is the electrical center of the dipole assembly. Since it is off center with

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respect to the reflector, the lobe produced will be off center. As the center of the dipole rotates around the axis of the reflector, the lobe is rotated also.

(3) The chief disadvantage of the method illustrated above is that the dipole assembly is not balanced mechanically about the axis of rotation. A second method has been used in which the dipole assembly closely resembles that of the system described in section IV. The coaxial line is at the center of the reflector, and is perfectly straight

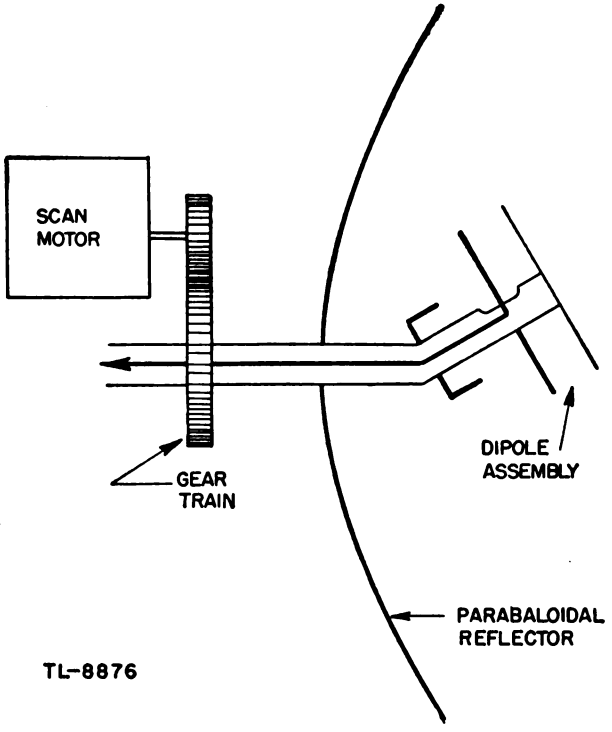

Figure 192. Off-center dipole.

and properly balanced. Figure 193 shows a dipole; elemant *A* is fed in the normal manner by direct connection to the inner conductor. The path for energy flow to element *B* is made longer by causing the energy to flow from the inside of the outer conductor through hole *C* and around the outside of the coaxial lines to element *B*. This manner of feeding, plus the position of the bazooka and the fact that the dipole elements are of different shape, gives an uneven current distribution. The uneven current distribution causes the electrical center of the dipole to move from the physical center. Therefore the energy is reflected from the paraboloid at a slight angle to the axis. As the dipole is rotated, the point at which the energy is directed describes

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a circle around the center of the reflector and the reradiated energy describes a cone giving the desired conical scan. The bazooka or quarter-wave balancing section mounted on the outer conductor of the coaxial line also prevents standing waves on the transmission line.

c. Waveguide conical scan. (1) It is possible to produce a relatively simple system of conical scanning with a round waveguide

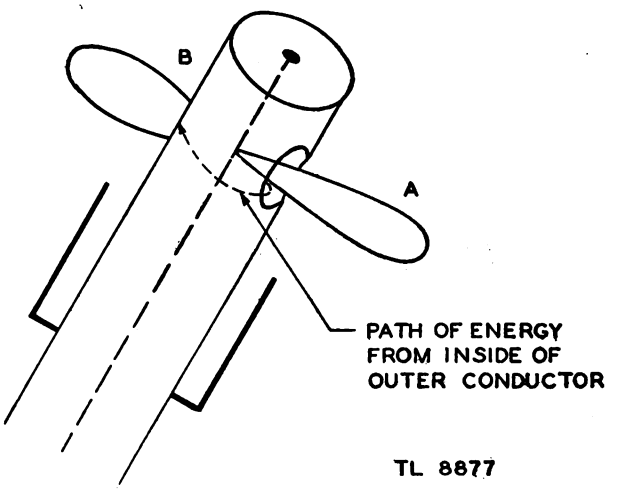

Figure 193. Construction of balanced conical-scan dipole.

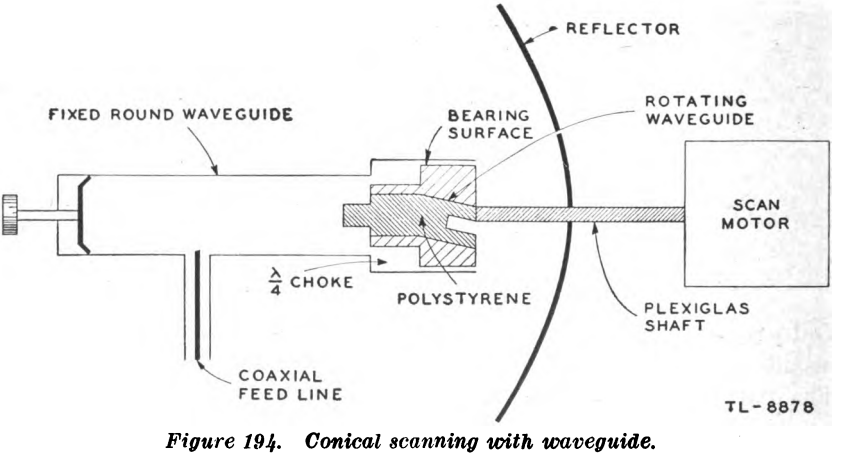

Figure 194. Conical scanning with waveguide.

which may easily be balanced mechanically. Figure 194 shows one type which is used. The r-f energy is supplied to a fixed round waveguide through a coaxial line. The inner conductor extends into the guide to act as the coupling probe, and a plunger in the end of the guide is used to adjust the degree of the coupling. A polystyrene-filled round waveguide is fitted in the other end of the waveguide.

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(2) The inner end of the polystyrene is of the proper size to match the impedance of the fixed waveguide to that of the rotating waveguide. The rotating waveguide is bent off the center line of the fixed guide in order to produce a beam shift by supplying energy off center to the paraboloidal reflector. The conical scan is produced by driving the offset rotating waveguide through a plexiglass shaft coupled to the scan motor. A small hole in the outer end of the polystyrene filling helps to match the rotating waveguide to the paraboloid and to free space.

(3) The system can be balanced by properly distributing the weight of the metal plug in which the hole is bored to form the rotating waveguide. Radiation through the rotating joint between the fixed waveguide and the metal plug is prevented by a groove a quarter-wavelength deep, which acts as an r-f choke.

41. NONDIRECTIONAL ANTENNAS.

a. General. There are a few applications of radar and its associated equipment that require the use of nondirectional antennas. This type of antenna is used where a bearing indication is not neces-

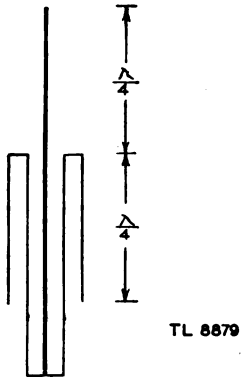

Figure 195. Vertical dipole fed with coaxial line.

sary or is undesirable. Nondirectional antennas are used in navigation aids such as beacons (Racon), some forms of IFF equipment, and in "presence" indicators, such as radar sets for submarines which indicate only the range of nearby aircraft.

b. Vertical dipole. (1) One of the simplest forms a nondirectional antenna can take is a single vertical radiator. It gives a uniform radiation pattern in the horizontal plane and a wide lobe in the vertical plane. Figure 195 shows one form of vertical dipole antenna fed by a coaxial line. The characteristic impedance of the line is designed to match the feed impedance of the antenna.

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(2) A J-type antenna is shown in figure 196. The radiator is a continuation of one leg of a quarter-wave matching section. The transmission line is matched to the antenna system by varying the position of the line on the matching section. The pattern of the J antenna in the vertical plane is slightly broader than the first-mentioned type of vertical radiator because of imperfect cancelation of the field of the matching section.

c. Turnstile antenna. (1) The turnstile antenna, figure 197①, gives a fairly uniform pattern in the horizontal plane and has the advantage of radiating horizontally polarized energy. The antenna is fed in such a way as to give a 90° phase shift between adjacent

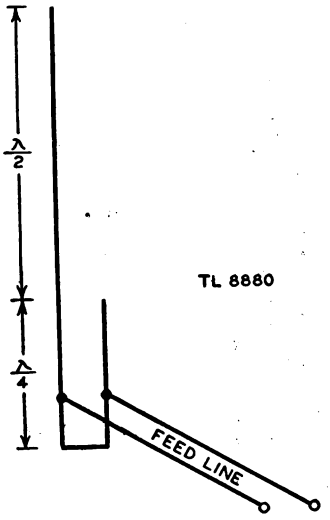

Figure 196. J-type vertical antenna.

radiating elements. The field strength broadside to one of the dipoles is equal to the field from that dipole alone. The field strength at a point at any other angle is equal to the vector sum of the fields from the two dipoles at that angle. The vector sum of the fields from both dipoles at any angle is nearly equal to the field strength when measured broadside to one dipole. Therefore, a nearly circular horizontal pattern is produced as shown in figure 197②.

(2) The feed system is shown in fig. 197①. Element *A* is fed from the center conductor of one concentric line and element *C* is fed from the outer conductor of the same line. Similarly, element *B* is fed from the center conductor of the other concentric line and the outer conductor of this line feeds element *D*. The characteristic impedance of each transmission line matches the input impedance of each of the crossed dipoles, hence standing waves are not present on the trans-

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mission line. In effect the two branches of transmission lines are fed in parallel at the tapped point T. The transmission line feeding this point must have one-half the characteristic impedance of the other lines or the impedance must be transformed by a matching section to prevent standing waves on the feed line.

(3) Since the length of the concentric line between points T and S is $\lambda/4$, the energy at point S is 90° out of phase with that at T. The distance from point S to dipole BD is the same as the distance from point T to dipole AC. Therefore element B lags element A by 90°.

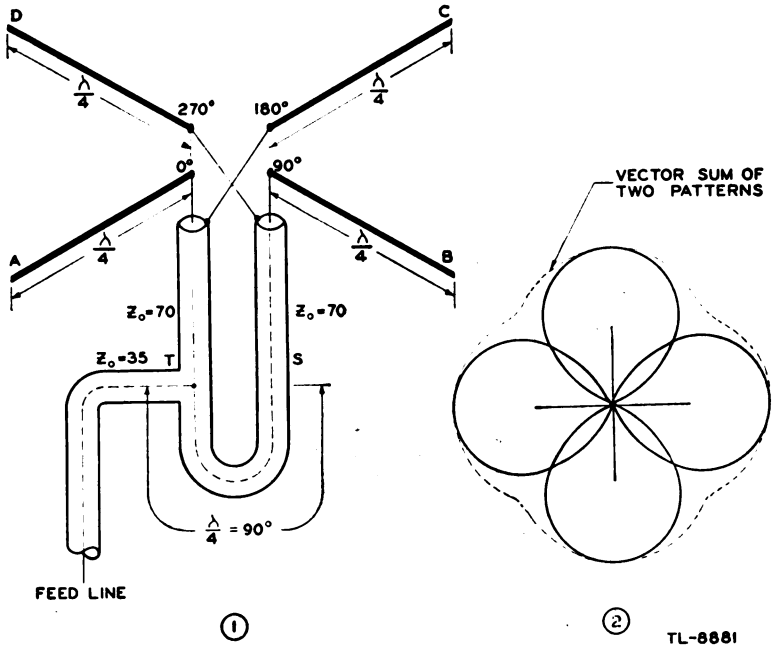

Figure 197. Turnstile antenna.

Likewise the energy fed to element D lags that fed to C by 90°. As a result, each element is 90° out of phase with the adjacent elements.

d. Other dipole configurations. (1) Figures 198 and 199 show two other antennas that may be used where a nondirectional pattern is desired.

(2) Figure 198 shows an antenna made of two half-wave elements, of which the end quarter-wavelength of each is bent back 90°. The pattern from this antenna is very much like that of the turnstile antenna. The field from the two quarter-wave sections that are bent back are additive because they are 180° out of phase and are a half-wave apart. The advantage of this antenna is the simplicity of its feed system and construction.

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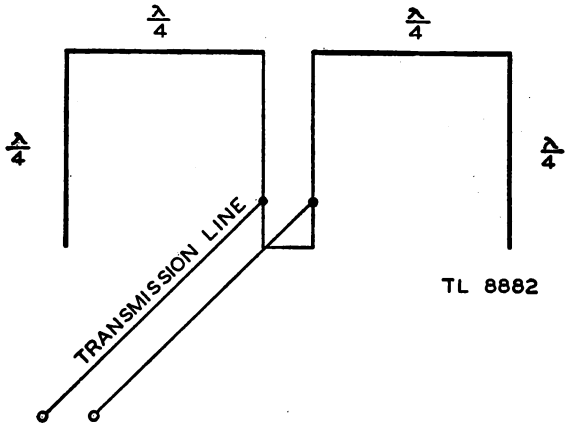

Figure 198. Bent-dipole antenna system.

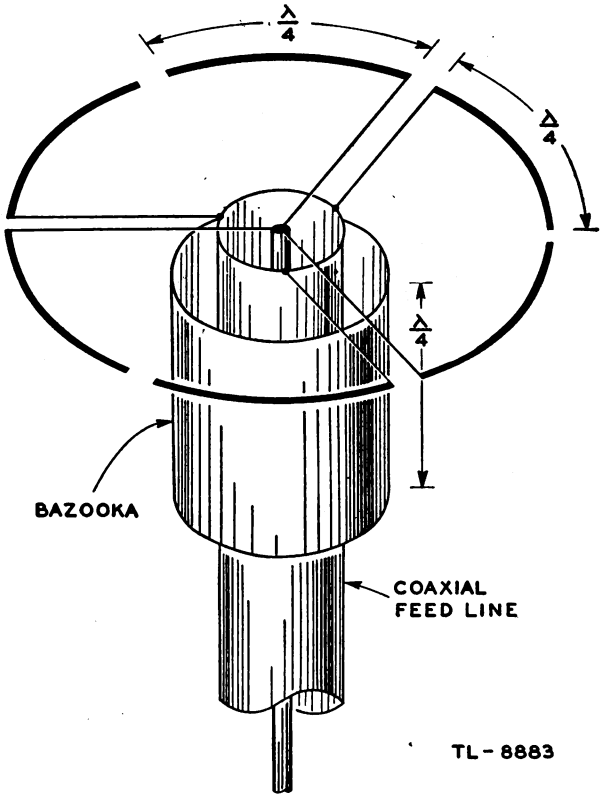

Figure 199. Antenna array of circular construction.

(3) Figure 199 shows an antenna with three dipoles bent to form a circle. All dipoles are excited in phase and the radiation is reasonably uniform in all directions. There is a little more interaction of the

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fields in this type than in the turnstile antenna. However, the interaction is uniform and does not detract from the effectiveness of this system as a non-directional antenna. The dipoles are center fed to match the impedance of the coaxial line. A bazooka is included in the system to prevent unbalance in the feeding of the dipole elements.

42. ECHO BOXES.

a. General. Echo boxes are resonant cavities designed to have a very high Q, of the order of 35,000. They are used with microwave radar sets to provide an artificial or "phantom" target which may be used to tune the receiver to the transmitter in case no real targets are available. The echo box may also be used to give an approximate

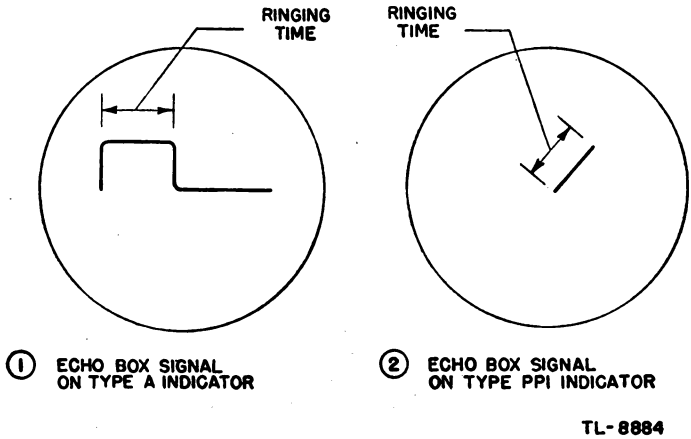

Figure 200. Appearance of echo-box signal on radar indicator.

indication of the transmitter output relative to some arbitrary standard, and if accurately calibrated, it may be used to measure frequency.

b. Theory of operation. (1) Energy from the radar antenna is fed into the resonant cavity to make it oscillate. Since the Q is very high, the cavity oscillates or rings for several microseconds after the end of the transmitted pulse. During the time that the echo box is ringing, it feeds energy back into the radar antenna, which produces an echo pulse on the indicator screen. The length of time that the echo box oscillates is dependent on the tuning and losses in the cavity, the pulse shape and peak power of the transmitter, and the tuning of the receiver. Since the echo box may be tuned to the transmitter under a given set of operating conditions, all variables except the receiver tuning may be eliminated. The receiver is then tuned by watching for maximum width of the pulse that appears on the indicator screen (fig. 200). False operation is prevented by designing the echo box so that it can oscillate in only one mode within the desired

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frequency band. The usual form is a cylindrical cavity one-half wavelength long that oscillates in the $TE_{0,1,1}$ mode.

(2) The echo box may be excited directly by pointing the antenna at a hole in the cavity. However, the echo box is more useful if it is mounted near the indicator, and the r-f energy is fed to it over a coaxial line which is connected to a dipole placed in the antenna field.

(3) An echo box may be improvised where a commercial type is not available. A well-tinned 1- or 5-gallon oil can gives an echo of approximately 3 miles width when properly tuned by denting the sides of the can until maximum response is observed on the indicator.

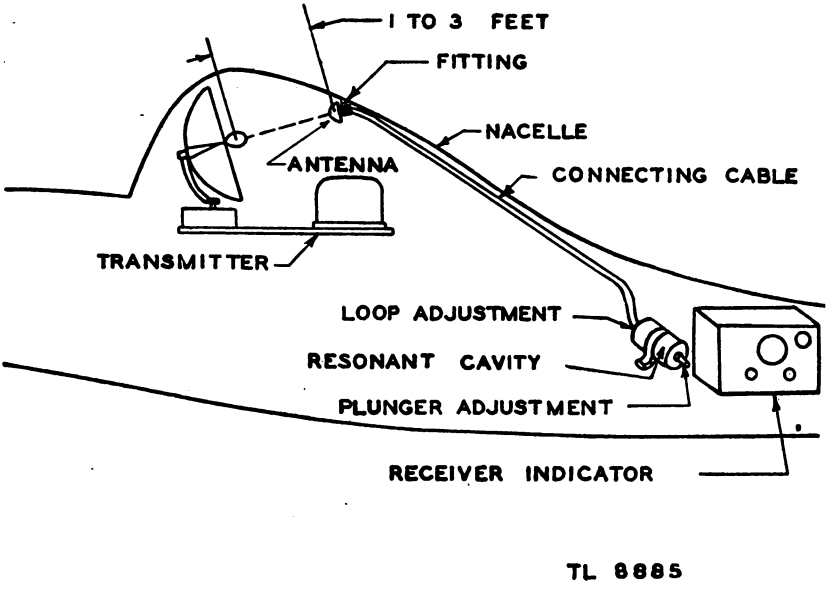

Figure 201. Echo-box test equipment mounted in aircraft.

Coupling to the system is obtained by removing the cap and pointing the hole in the can at the radar antenna. The can should be held 4 to 5 feet in front of the antenna to prevent overloading of the receiver.

c. Tuning by means of echo box. (1) Tuning by means of permaent echoes can be satisfactorily accomplished where an A-scope is available. When the only scopes available are type B or PPI, tuning on permanent echoes requires judging the brilliance of the pattern. This is extremely difficult because of the long persistence screen on such scopes. Therefore, some form of echo box is desirable because it shows by an increased width or range of echo pulse an improvement in performance resulting from an increase in transmitter power or from improved tuning of the receiver. The

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echo box is also useful with an A-scope because it gives a reference echo that does not change with location or other conditions. Figure 200 shows the returned signal on an A-scope and PPI-scope. In some plane and ship installations where there is the possibility that no permanent echoes will be available, echo boxes are an integral part of the installation, as shown for an aircraft in figure 201. The echo box or pickup antenna is mounted at a point where pickup may be obtained from the radar antenna. During the normal operation of the set the echo box is either detuned or disconnected from the pickup antenna.

(2) An echo box may be used for other purposes by adding a second pickup loop and coupling a crystal detector and microammeter to it. With these additional components it is possible to calibrate the echo-box dial for use as a wavemeter. An instrument of this type is useful in transmitter adjustment because receiver tuning does not enter the picture.

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Section VIII
Receivers

43. GENERAL.

a. Introduction. Improved receiver design can increase the usefulness of radar equipment, perhaps more than any other single factor. Only a small part of the energy radiated from the antenna strikes a distant target, in spite of efforts to limit the transmitted energy to a narrow beam. The reflections from the target are scattered in random directions, causing the echo which returns to the set to be extremely small. The receiver must accept signals of perhaps a microvolt or less in amplitude and amplify them to useful magnitudes. The effective range of a radar set is therefore proportional to the ability of its receiver to utilize weak reflected signals. The weaker the signal which the receiver can use, the greater the effective range of the set.

b. Signal-to-noise ratio. (1) Theoretically it is possible by using many stages of amplification to build any signal, no matter how weak, to any desired amplitude. However, there are present in all electrical circuits various random disturbances which produce small voltage variations known as noise. In particular, the input stage of the receiver generates such voltages. These are amplified along with the signal voltage in the following stages of the receiver. Noises are generated in the other stages, but these are less important since they are not amplified as much as those which are present in the first stage. If the signal is not at least as large in amplitude as the noise voltage at the input stage, it cannot be recognized at the receiver output and therefore is useless.

(2) A primary consideration in receiver design is to keep the noise level as low as possible so that, for a given signal, the signal-to-noise ratio is high. If the noise level is low a weak signal from a distant target may be detected. If the noise level is high the target has to be much closer before the echo from it is sufficiently strong to override the noise. Thus the noise generated in the receiver is a factor which affects the useful range of the set. Reducing noise by improved design on a moderately good receiver may extend the range of the set much more effectively than increasing the output power of the transmitter.

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(3) The noises which are generated in an amplifier stage include three types. These are thermal agitation, shot effect, and induced noises. All of these include frequency components throughout the entire frequency spectrum, and the amount of noise therefore is affected by the choice of bandwidth for the receiver. (See sec. IV.) In general, a reduction in bandwidth of the receiver reduces the noise voltage, but does so at the expense of pulse shape. The amount of distortion of the pulse shape which can be tolerated is the limiting factor in increasing signal-to-noise ratio by reduction in bandwidth.

(4) Thermal agitation noises are caused by random motion of free electrons in a conductor. At any instant there are likely to be more electrons moving in one direction than in the other, causing a voltage to develop across the conductor. If the temperature of the conductor rises, the agitation of the electrons increases in both directions so that the instantaneous current is greater. Since the noise voltage generated in a conductor is the IR drop from this current, the amplitude of the noise voltage increases with an increase of either temperature or conductor resistance.

(5) Shot effect is caused by irregular emission from the cathode of a tube. The electron flow in the plate circuit varies slightly in the number of electrons reaching the plate from one instant to another, and in the velocities of the individual electrons. This very small current variation produces a small voltage variation across the load impedance of the tube which is known as noise, since the irregularities are entirely random. When a positive grid is placed in the electron path to divide the electron flow with the plate, the shot effect is magnified because the division of the electrons is also irregular. For this reason multigrid tubes are noisier than triodes. Shot effect can be minimized by using a high mutual-conductance tube, since the signal control of the electron stream is greater than in a low mutual-conductance tube for the same relative noise level. An increase in the space charge by higher filament temperatures is sometimes helpful in smoothing out emission variations.

(6) Stray electrostatic and electromagnetic fields may induce voltages and currents in resistors, leads, and even within the tubes themselves. In addition to the shot effect in the plate circuit, the irregular electron stream causes currents to flow in the grid circuit. The electrons moving past the grid induce charges on it which are dependent on the positions of the electrons. If the flow is constant in velocity and number of electrons, the net result of all electrons will be constant. Actually this is not true, so that a random variation in charge on the grid occurs, with a resulting movement of electrons to and from the grid circuit. This takes place without electrons from the cathode reaching the grid, but by merely passing by. The movement of elec-

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trons in the grid circuit produces a noise voltage across the grid circuit which is amplified by the tube. The magnitude of the noise voltage on the grid resulting from the electron stream increases with frequency, so that noise from this source depends both on bandwidth and the carrier frequency. Any other stray fields external to the tube may produce similar effects, in addition to voltages produced by insufficient filtering of the plate voltage supply. Long feed lines are particularly susceptible to stray fields. Induced noise voltages are minimized by low impedance circuits, shielding, filtering, and short leads.

c. R-f amplifiers. (1) The difficulty of obtaining useful amplifications becomes greater as the carrier frequency becomes higher. Because of noise considerations, screen grid tubes, which are in common use at broadcast and lower radar frequencies, are less useful at the higher radar frequencies. The inductive reactance of the cathode leads at these frequencies causes appreciable degeneration. The signal voltage and part of the noise voltage are affected equally by this degeneration. The noise resulting from random division of current between the plate and screen grid, however, is not affected, because both of the currents flow in the cathode. The result is an over-all reduction of signal-to-noise ratio.

(2) At extremely high frequencies, the capacitive reactance between tube elements becomes important. In triodes the grid-plate capacitance tends to cause instability which may set up oscillations. The grid-to-cathode capacitance tends also to shunt the signal voltage. The result is to limit the possible gain of the tube. The factors affecting the ability to produce amplification have been discussed in section III.

(3) It was pointed out in b(6) above that the irregular emission of the cathode caused an apparent flow of current in the grid circuit without electrons reaching the grid from the cathode. This produces an input resistance to the tube which loads the grid circuit. The higher the carrier frequency, the lower is this input resistance. The electron stream is varied by the applied signal voltage as well, and this lowers the apparent input resistance. Thus the physical grid circuit constructed from inductance and capacitance is paralleled by the apparent input resistance and capacitance of the tube.

(4) For the above reasons, r-f amplifiers have not been used extensively in the microwave region. At the lower radar frequencies, more or less satisfactory gain has been obtained by using tubes of small physical size to reduce interelectrode capacitance and the electron transit time. Multiple short leads to the cathode have been used in an attempt to reduce the inductance. A circuit with the grid grounded and the signal applied to the cathode is also useful in extending the high frequency limit of r-f amplifiers since the plate-to-grid

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capacitance then acts only as a load on the plate circuit, rather than as a feedback path as in a conventional circuit.

(5) A tube which lends itself well to the grounded-grid type of circuit, or to circuits using tuned concentric lines, is the lighthouse triode. The heater and cathode connections are made to pins in a standard octal tube base. The plate connection is made to the cap, and the grid connection is made to a ring encircling the tube about halfway between the cap and the shell. This construction allows the tube to be made rugged with less interelectrode capacitance for the small spacing than in conventional triodes. A circuit using this tube as an r-f amplifier is shown in figure 202. The coaxial cable carrying the signal is connected directly to the cathode shell. The signal voltage which appears across the tuned cathode circuit C1, L1, is coupled to the cathode by the capacitance between the cathode and shell. Since the grid is grounded, the application of a signal to the cathode controls the plate current of the tube. Bias is developed across resistor R1. The plate coil L2 is tuned to resonance by capacitor C2. A filter network L3, C4, C5 bypasses to ground any r-f in the plate voltage lead. The resistors R2 and R3 permit the adjustment of the operating voltage to the proper value of from 200 to 250 volts.

(6) Another r-f amplifier using a lighthouse triode and tuned by concentric lines is shown in figure 203. The r-f input is tapped directly on the grid line. The cathode is coupled to the outer conductor of the grid cathode line by the capacitors C7 and C8 which are built into the tube, and bypass radio frequency from the metal shell that forms the base of the tube to the cathode. Grid bias is furnished by the potentiometer R1 which is set to give the correct plate current. Plate voltage is supplied through the filter made up of C4, C5, and R3 located inside the plate line. Coupling to the next stage is made by means of a pickup coil positioned between the grid and plate lines. Because of the grid plate line some regenerative amplification may be realized. Oscillation is prevented by proper loading and location of the grid input tap.

d. Blocking and recovery time. (1) The receiver, though partially protected by a T-R device, receives a strong signal directly from the transmitter. This signal may overdrive and block the receiver and render it insensitive to signals which follow shortly afterward. Thus the minimum range may be seriously impaired by the receiver's inability to detect signals from nearby targets. The blocking results from excessive bias developed on one of the tubes by the signal, usually in a video stage which is resistance coupled. The blocking bias may be developed by grid current, or by excessive current through a cathode biasing resistor if it is bypassed by a capacitor. The stages preceding the second detector are not usually subject to

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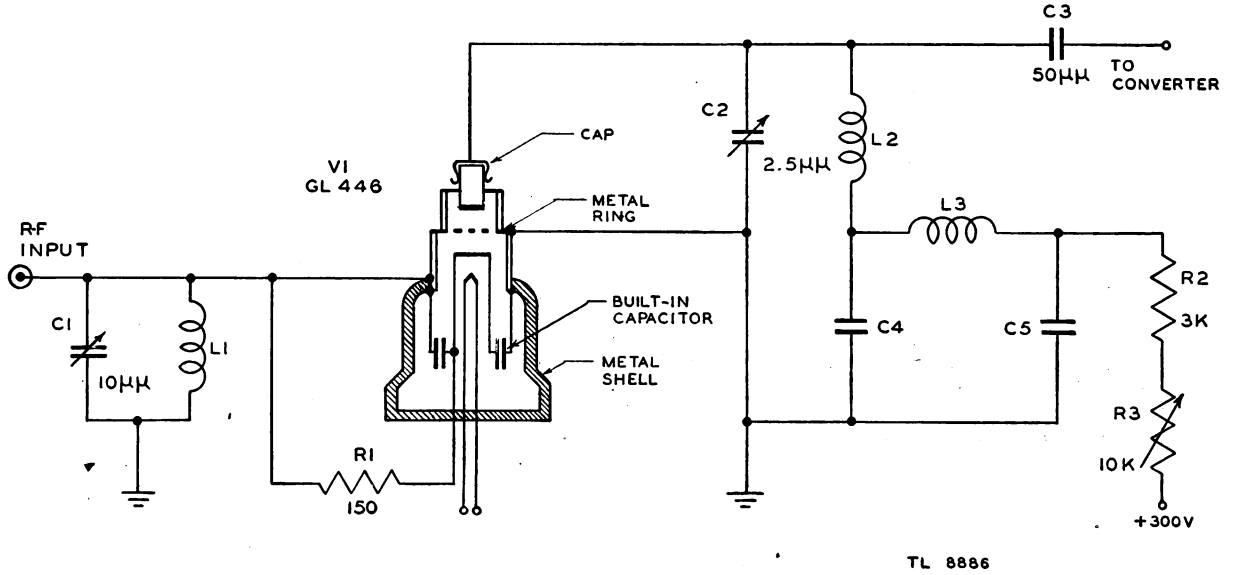

Figure 202. Grounded-grid r-f amplifier.

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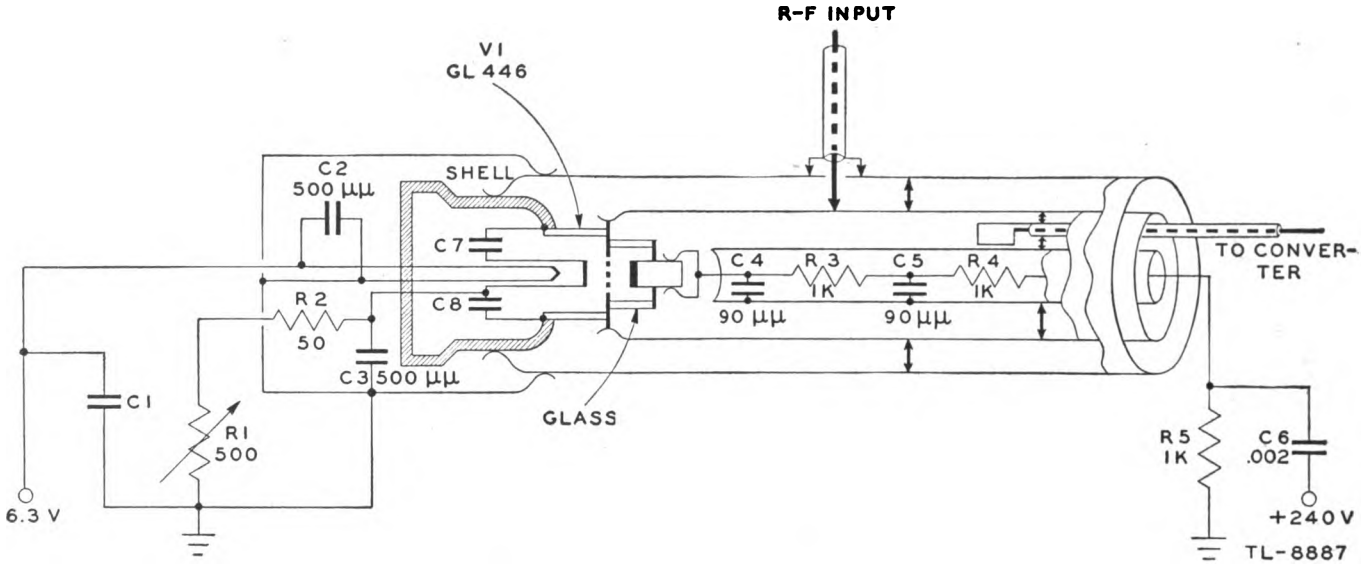

Figure 203. R-f amplifier with lighthouse tube.

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blocking because the signal has not been amplified sufficiently to overdrive the tubes, since inductors rather than resistors are used in the grid leads, and because any cathode biasing resistors are unbypassed.

(2) Blocking in the video stages can be prevented, or its effect minimized, in several ways. A gate pulse applied to one or more of the i-f stages may either bias the tubes to cut-off or remove the supply voltage for the duration of the transmitted pulse. When it is necessary to receive weak signals at the earliest possible moment after the transmitted pulse, as in AI equipment, gating is used. If the second detector produces negative pulses, the first video stage may be used as a limiter. Any signal of too great amplitude merely drives this tube to cut-off and its output is limited to a predetermined maximum amplitude. If the bias is supplied from the power supply through a voltage divider which draws a large current, any excess conduction by the tube produces only a negligible voltage change in the biasing resistor. When blocking does occur, its duration is determined by the time constants involved. The effect can be made less objectionable by making the time constants, and consequently the recovery time, as short as is practicable. By leaving the cathode resistor unbypassed, its time constant is made practically zero.

44. AUTOMATIC FREQUENCY CONTROL.

a. General. Any frequency drift of the carrier or local oscillator causes the intermediate frequency to change by the same amount. To compensate for this drift the i-f bandwidth may be increased in the design of the receiver. This increase in bandwidth will raise the noise level, but if the increase is not made, the pulse will be distorted owing to loss of high frequency components. The performance of the receiver can be improved by automatic frequency control which avoids both difficulties. If the intermediate frequency changes for any reason, the control circuit brings it back to its proper value by tuning the local oscillator.

b. Operation. (1) In the circuit of figure 204, the input signal is at an intermediate frequency of 60 megacycles. A drift of the intermediate frequency produces a d-c voltage change which, after amplification, is impressed on the repeller grid of the klystron oscillator to retune it to the correct frequency. Tube V1 is an i-f amplifier, where input comes from the regular i-f channel. The secondary of transformer T1 is tuned to resonance at the i-f frequency. The coupling of the primary and secondary, and the tuning of the primary are adjusted to give a voltage across the secondary that differs by 90° in time phase with the primary voltage. The primary is connected to the center tap of the secondary by means of the coupling condenser C4.

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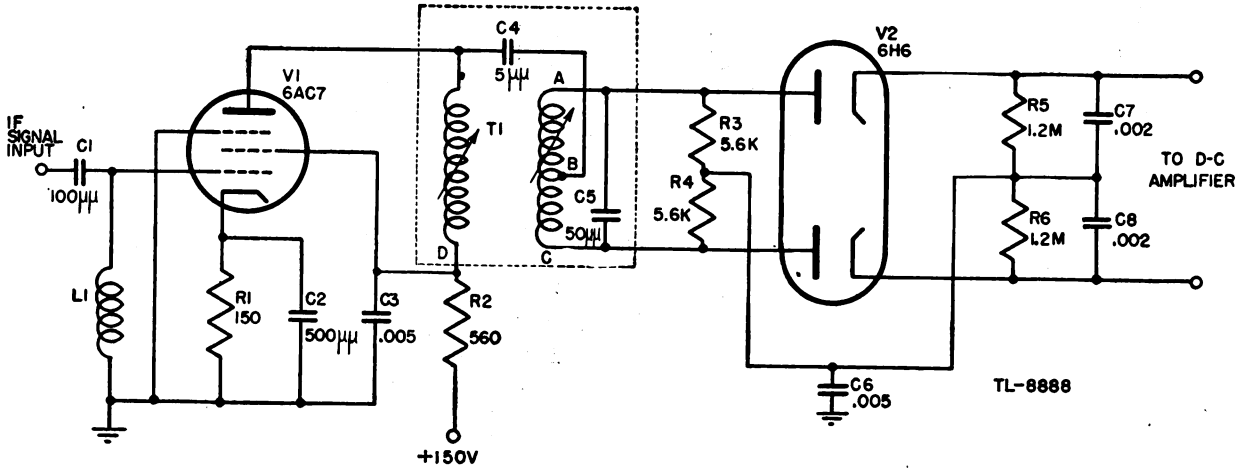

Figure 204. Frequency discriminator.

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(2) Figure 205 shows an equivalent circuit of the discriminator and the various voltage relations for frequencies above, below, and at resonance. As shown in the equivalent circuit, ①, the voltage applied between the upper diode plate and cathode is the drop across the resistor between *A* and *D*. This is the vector sum of the voltage across the upper half of the secondary, *A* to *B* and the voltage of the primary, *B* to *D*. Similarly, the voltage applied to the lower diode plate is

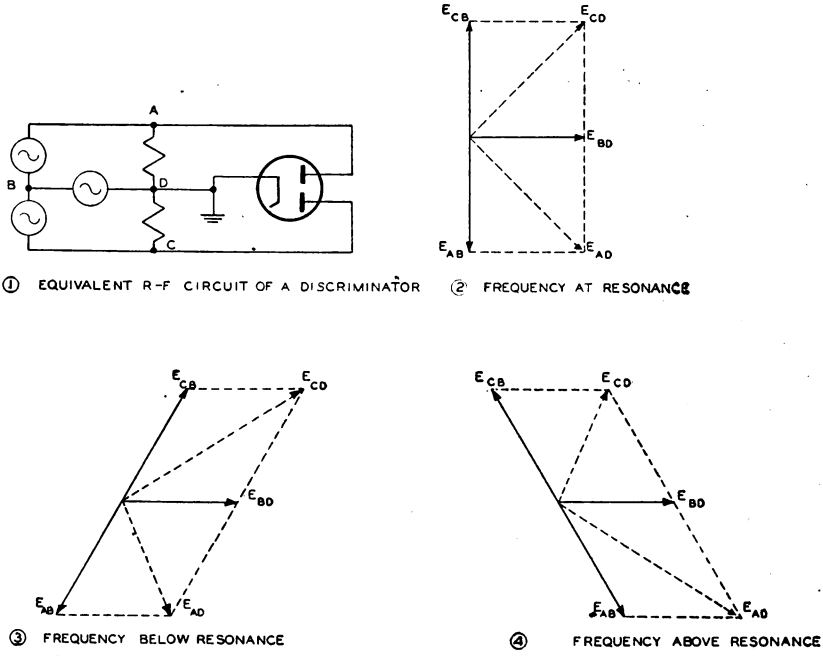

Figure 205. Vector diagrams and equipment circuit of discriminator.

that across the lower half of the secondary, *C* to *B* plus the primary voltage, *B* to *D*.

(3) When the i-f signal is at its proper frequency, the voltage across the secondary, *A* to *C* is 90° out of phase with the voltage across the primary, *B* to *D* (fig. 205②). Thus *ECB* leads *EBD* by 90°, while *EAB* lags *EBD* by 90°. Since the secondary is center-tapped to make *EAB* equal to *ECB*, the vector sums are equal in magnitude. Equal signals on the two diode plates produce equal currents in the cathodes, which in turn produce d-c voltage drops across R5 and R6 which are equal but of opposite polarity. The output to the d-c amplifier is therefore zero.

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(4) If the i-f signal changes in frequency, the secondary circuit is no longer tuned to resonance, and voltage *A* to *C* no longer differs by 90°. If the frequency decreases, a lag of more than 90° is produced; if the frequency increases, a lag of less than 90° occurs. In the former case the voltage applied to the lower diode plate is greater (3), and the output to the d-c amplifier is negative. In the latter case conditions are reversed (4), and a positive output is produced. After being amplified, the d-c voltage is used to correct the klystron, or local oscillator frequency.

45. SUPERREGENERATIVE RECEIVERS.

a. General. Superregeneration takes place in an oscillator when oscillations are started and stopped at a radio frequency rate that is low in comparison with the frequency of the generated oscillations. This effect can be accomplished by applying a quench voltage in the lower radio-frequency range (25 to 300 kilocycles) to the grid or plate circuit of an oscillator in such a way that the tube oscillates only during a portion of the positive half cycle of the quench voltage. The oscillations build up during the positive half cycle only to be suppressed or quenched as the low frequency voltage drops to value at which oscillations cannot be sustained. When a superregenerative oscillator is used in a receiver the incoming signal is impressed on the grid of the superregenerative stage. Since the tube is in an extremely high regenerative condition during the periods of oscillation the amplification obtained is very great. Superregenerative receivers are very simple in design when compared with superheterodyne receivers and they are utilized in some instances where weight is an important factor.

b. Superregenerative receiver circuit. (1) A simplified diagram of a superregenerative receiver using a triode oscillator and a diode rectifier or detector is shown in figure 206. Regeneration or feedback from the plate to the grid takes place through the oscillator tank circuit. Capacitors C1 and C2 couple the grid and plate of the tube to the tank circuit. Plate voltage is supplied through L2 and the power supply is bypassed by capacitor C3. Grid bias and the quench voltage are applied to the grid of tube V1 through L4, which offers a high impedance to the high resonant frequency of the oscillator, but is low enough to pass the quench frequency. Resistor R1 is a sensitivity control that varies the d-c bias on the oscillator V1. R2 serves to give the oscillator some self bias and limits the speed at which oscillations build up.

(2) The output of the oscillator is taken from the tank circuit and coupled to the rectifier or detector tube V2 by means of capacitor C4. L5 and R3 form the load of the detector and the output appears across R3.

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c. Operation. (1) The operation of the receiver when no signal is applied is shown diagrammatically by the voltage curves in figure 207. The noise that is generated as a result of shot effect and thermal agitation is shown in curve ①. Curve ② shows the effective

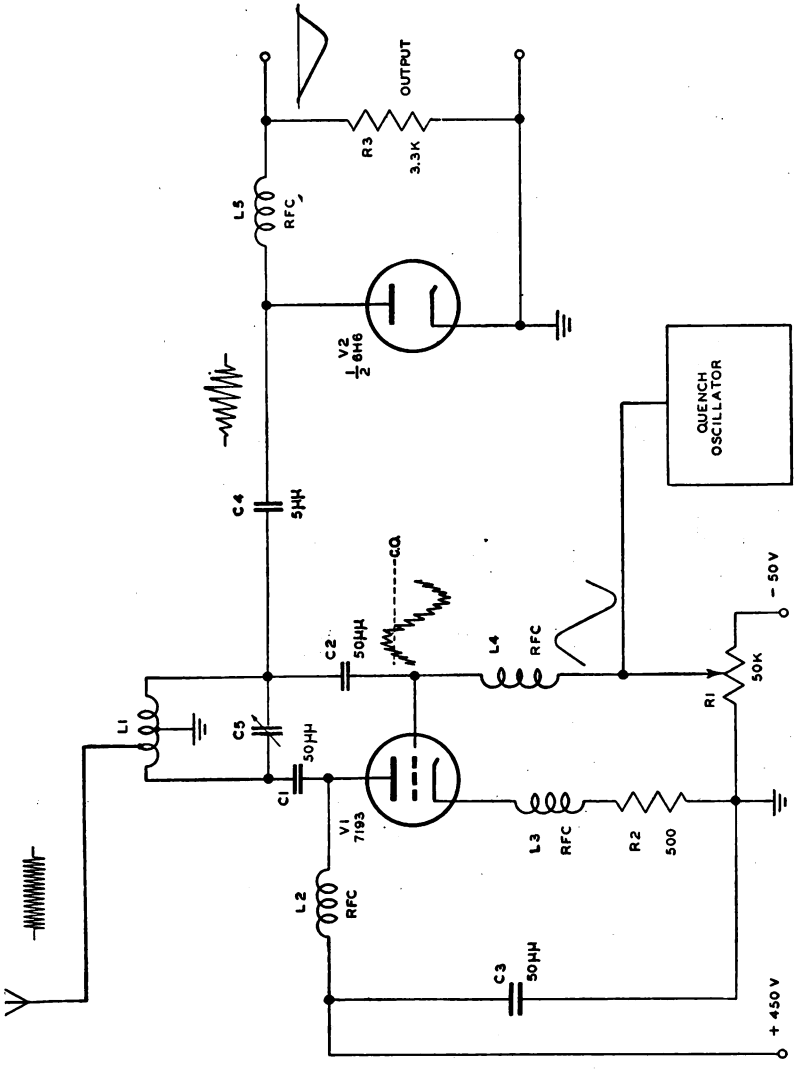

Figure 206. Schematic diagram of a superregenerative receiver.

noise voltage mixed with a quench voltage applied to the grid. The amplitude of the noise voltage as shown is extremely exaggerated for illustrative purposes. The d-c bias applied to the superregenerative oscillator is high enough to prevent it from oscillating until the quench voltage is applied. The amount of this bias determines the points on the quench cycle between which the tube oscillates. Curve ③

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shows how the oscillations started by a noise voltage build up, and curve ④ illustrates the rectified output from the detector stage. It can be seen that though no signal is being received there is a small output from the detector stage. It can be seen that though no signal is being received there is a small output from the detector made up

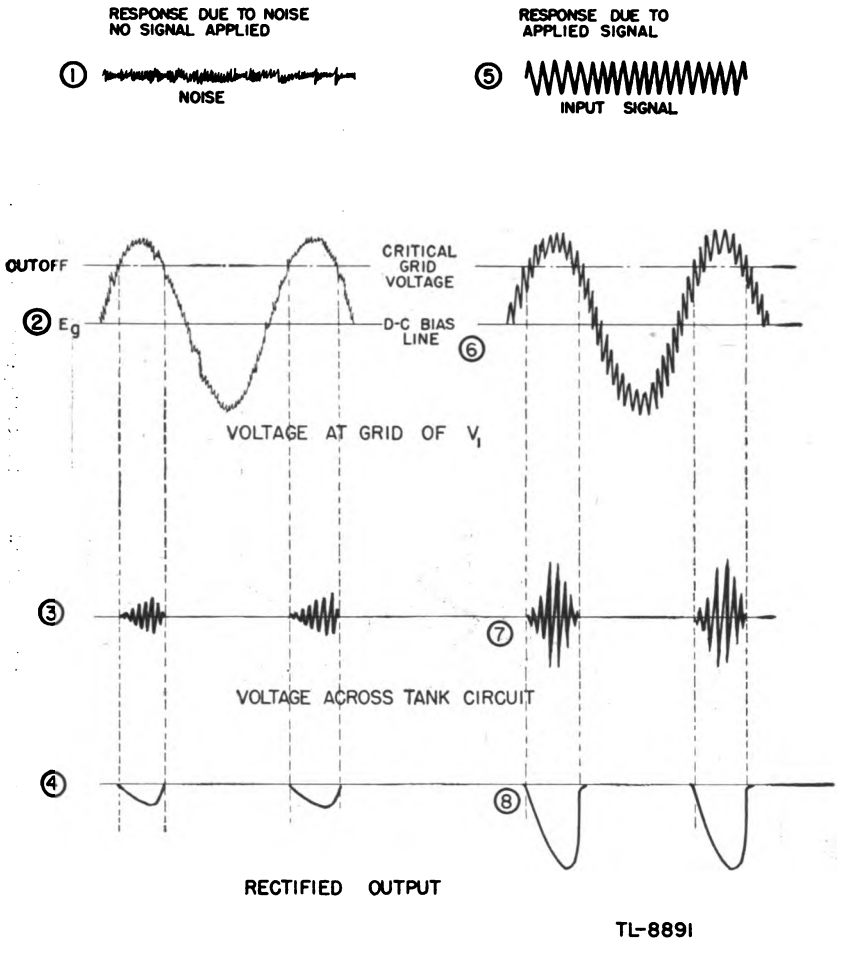

Figure 207. Voltages developed in a superregenerative receiver.

of pulses occurring at the quench frequency. When oscillations are started by the noise voltages in the circuit, the speed at which oscillations build up depends upon the magnitude of the noise at that particular instant. Since there is a great chance factor in noise amplitude, the time oscillations start and the speed at which they build up varies greatly, producing the hiss that is characteristic of superregenerative receivers.

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(2) The action of the receiver when a signal is applied is illustrated in curves ⑤ to ⑧. Curve ⑥ shows the input signal mixed with the quench voltage. It can be seen that the grid reaches its critical bias earlier in the quench cycle when there is a signal applied. This occurs because the peaks of the input signal drive the grid of the tube above the critical point. Also the voltage on the grid falls below the critical point later in the quench cycle when a signal is applied. Consequently oscillations reach a greater amplitude before being quenched and are produced in the receiver for a longer time. For this reason the output is much greater when a signal is being received than in the normal no-signal operation. The characteristic hiss is eliminated when the signal is applied because oscillations are started by the peaks of the r-f signal voltage giving a definite recurrence time. The noise voltage is extremely small when compared with the usual signal so that it has practically no effect on the time oscillations start.

(3) The sensitivity control, R1, shown in figure 206 determines the point on the quench voltage wave at which the tube will oscillate. The time the tube is in a regenerative condition is determined by the grid bias and the frequency of the quench voltage. When a superregenerative receiver is used where pulses are to be received, the grid voltage is adjusted to a compromise value between maximum sensitivity and a value at which the output pulses resulting from noise are not large enough to interfere with the function of the set.

(4) The diode V2 functions as a detector. During the positive half cycles of the radio frequency the impedance of the tube is extremely low and very little voltage appears across the load L5 and R3. The coupling capacitor C4 is extremely small and prevents excessive loading of the superregenerative stage during the half cycles that the detector is conducting. During the negative half cycle the diode V2 does not conduct, and therefore considerable r-f voltage appears across L5 and R3. The negative pulses of r-f voltage cause current to flow through L5 and R3. The action of L5 is to store up energy during the peaks of the r-f pulses and to release it between r-f pulses to keep the current flowing in the same direction. The result is to produce a d-c voltage across R3 during received signals in the form of pulses as shown in figure 207 (8).

46. AUTOMATIC GAIN CONTROL.

a. General. (1) The amplitude at the input to the receiver of the echo from a particular target may vary because of fading and changing of the position of the target at a more or less rapid rate. If the receiver has a constant gain there is a corresponding variation in the amplitude of the output. If this changing amplitude is objectionable, as in systems where the signal is used for automatic

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tracking, an automatic gain control may be used to give greater gain when the signal is weak than when it is strong. Thus the amplitude at the output is maintained relatively constant.

(2) A common type of automatic gain control, which is in use in commercial receivers, uses the signal voltage to control the bias on one or more tubes. A d-c voltage obtained by rectifying the signal is used for this purpose. If the signal is too strong the grid of the amplifier tube is made more negative to reduce the gain. A remote cut-off tube is used to prevent excessive distortion.

(3) The voltage developed from the signal may be used to control the gain by letting it regulate the supply voltage for the plates and screen grids of amplifier tubes. When this method is used, several stages of d-c amplification are needed to furnish the AGC voltage, the last stage being a power amplifier.

(4) In radar sets where automatic gain control is used, the voltage is developed from a particular target under observation, since the signals from all targets vary independently of each other. For this reason, a signal selector circuit chooses the interval of time which includes the echo from the desired target. Only the signal received during this brief time interval influences the receiver gain. Thus echoes from targets at ranges appreciably different from that of the selected target have no effect on the gain.

b. Typical AGC Circuit. (1) A circuit which provides automatic gain control based on the signal returned from a single target is shown in figure 208. The operator places a range gate or notch under the echo pulse of the target to be tracked on the indicator. He adjusts continually the position of this gate to the movement of the target. An AGC gate, which occurs simultaneously with the range gate, is applied to tube V1 to select the proper echo pulse from the receiver output. The output of V1 is amplified and inverted, rectified, amplified by a three stage d-c amplifier, and applied to the receiver as screen and plate voltage.

(2) Tube V1 is a pentagrid converter tube to which is applied the AGC gate pulse, and the output of the receiver. In the absence of gate and receiver output, V1 is biased beyond cut-off. The gate pulse is adjusted in amplitude to make V1 barely conductive. The receiver output is not large enough to cause the tube to conduct. When an echo signal and the gate occur simultaneously, the echo signal is amplified. All other echo signals are lost because V1 is nonconducting except during the gate.

(3) The selected signal is amplified and inverted by tube V2 to produce positive pulses. V3 is a diode detector which rectifies the pulses to produce an approximately steady positive d-c voltage across

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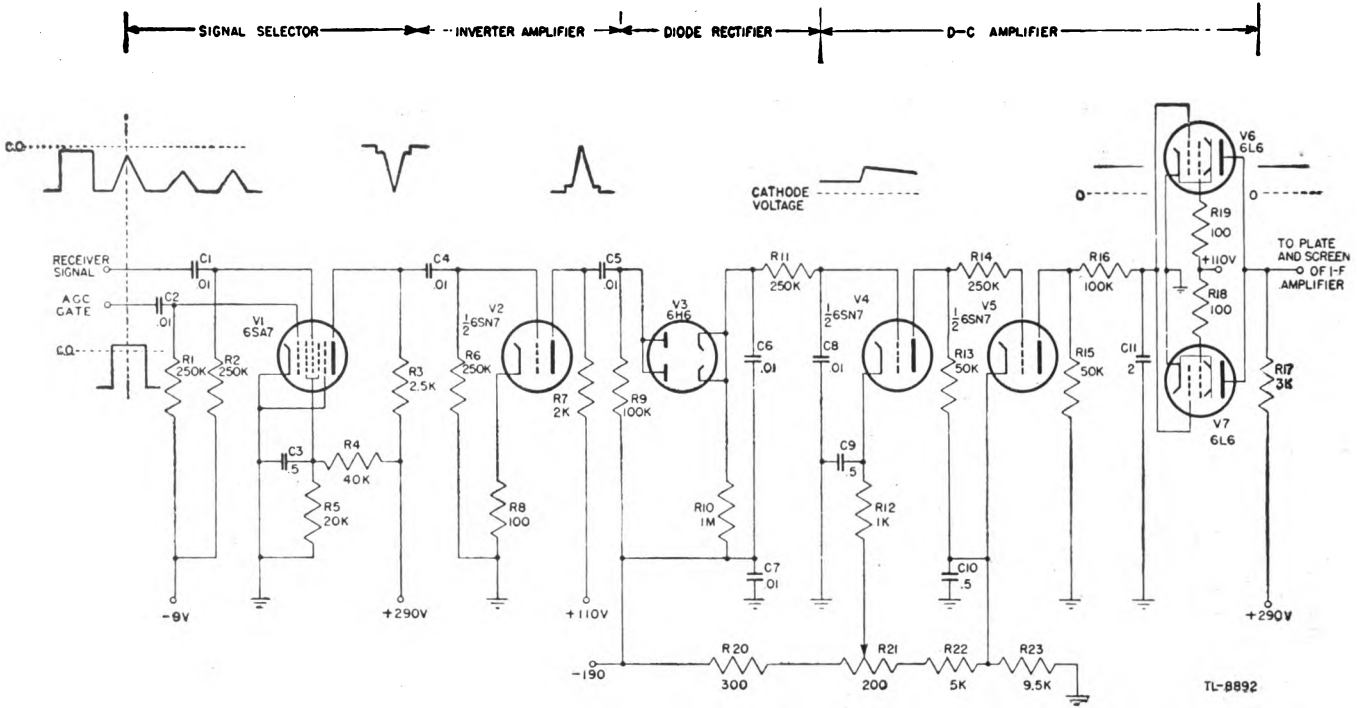

Figure 208. Automatic gain control.

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the filter *R10* and C6. The magnitude of this voltage is proportional to the strength of the r-f signals returned by the target being tracked.

(4) The output of the diode is applied directly to the grid of V4 which in turn is directly coupled to the grid of V5. In order to obtain direct coupling in these tubes, and to the parallel amplifier, V6 and V7, the required voltages for these tubes are obtained from a voltage divider, resistors R20, R21, R22, and R23, connected to −190 volts. Capacitors C8, C10, and C11 remove any pulse ripple to produce a steady d-c voltage.

(5) The plate voltage of V6 and V7 depends on the magnitude of the echo signals received from the chosen target. If the signals are large, these tubes draw a heavy plate current, and their plate voltage is low. If the signals become small, the plate current becomes small and the plate voltage rises. The plates and screens of the i-f amplifiers are connected to the plates of V6 and V7, so that the gain of the i-f amplifier is controlled directly by signal strength.

(6) The speed with which the AGC circuit responds to a change in signal strength is fixed by the time constants of the R-C filters used to remove ripple. These are set so that successive pulses can be received with little change in the d-c output voltage so long as their amplitudes are equal. If the average value of the pulses change, however, the result is to produce a change in the d-c output which will correct the gain of the i-f amplifier to return the selected signals to their proper value.

47. TUNING INDICATOR.

a. General. In some cases it is difficult to tune a receiver exactly to the frequency of the transmitter. This occurs in cases where an A scope is not provided. The tuning indicators in general use are operated by the average voltage of all signals being received. In the usual circuit the output of the i-f section is rectified, filtered, and applied to a sensitive indicator. The indicator may be either a sensitive d-c meter or an electron-ray tube. Where only an instantaneous indication of maximum signal is desired and relative measurements are not necessary an indicator of the magic eye type is used because it is much less expensive than the meter type.

b. Magic eye. The magic-eye type of indicator is basically a cathode-ray device in which the electrons emitted at the cathode are attracted to the fluorescent target, causing it to glow. A sketch of a magic eye-tube is shown in figure 209. A ray control electrode is placed on one side of the cathode and casts an electrical shadow on the screen. The width of the shadow depends upon the d-c voltage on the control electrode. The output of the rectifier or detector could be applied directly to the control electrode, but usually an amplifier

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stage is used. The amplifier may be either external or built into the indicator tube itself.

c. Circuit analysis. A diagram of an electron-ray tube circuit is shown in figure 210. The output of the detector is such that the voltage applied to the amplifier grid becomes more negative as the

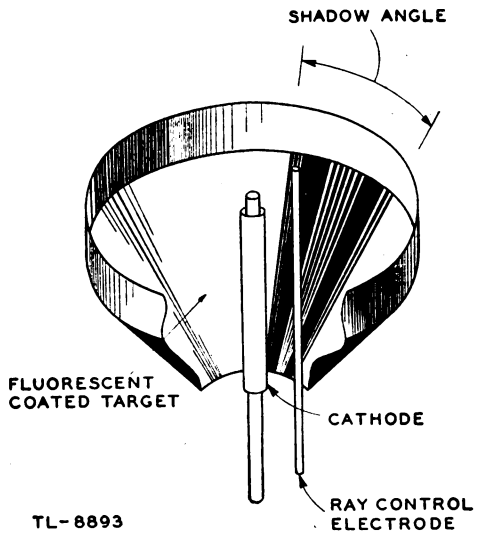

Figure 209. Magic-eye type of indicator tube.

signal voltage increases, causing the potential of the amplifier plate and the control electrode which is tied directly to the plate to rise as the signal increases. When the potential on the control electrode increases the electrons passing the electrode are deflected less and the shadow angle is decreased.

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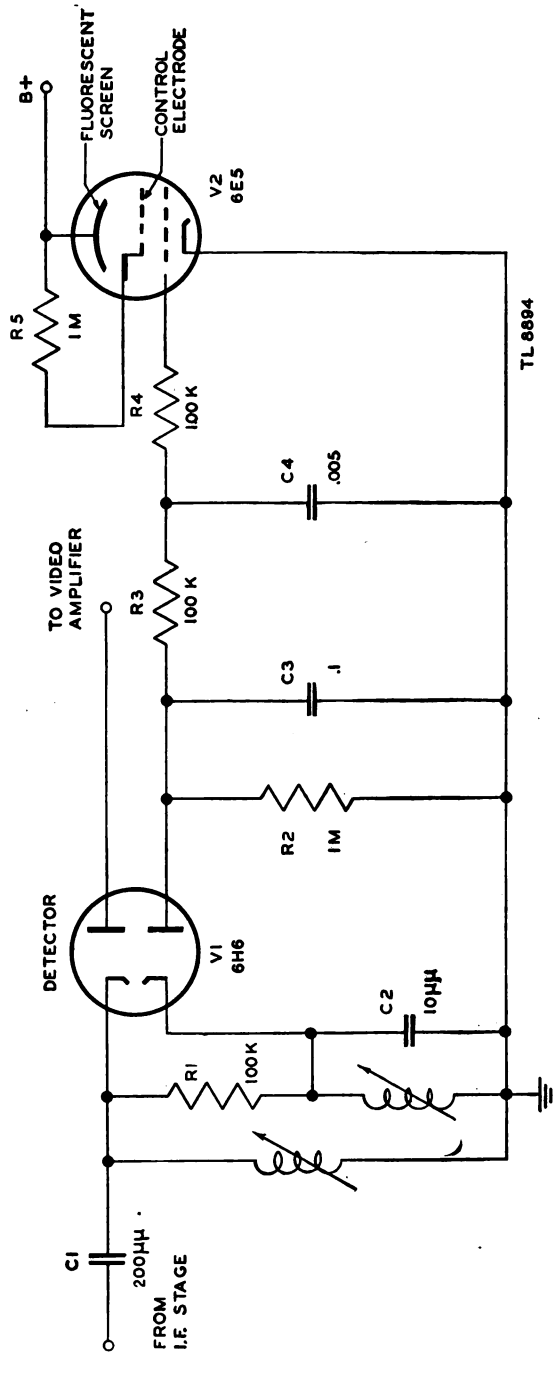

Figure 210. Circuit diagram of an electron-ray tuning indicator.

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Section IX
Indicators

48. GENERAL.

a. Types of scan. (1) The basic types of data presentation were briefly described in section II. The use of one or more types of scan in a radar set is governed by the application to which the set is to be put. As more and more uses are found for radar, the indicators are modified from the simple basic types of scans to more complex scans which fulfill special needs by presenting all necessary data on one oscilloscope.

(2) In search or early-warning sets it is desirable to view as large an area as possible and to track several targets simultaneously. For this application the PPI-scan is very useful, and it is frequently supplemented with an A-scan so that the character of the echo may be carefully observed and both ranging and identification may be accomplished easily.

(3) In fire-control or gun-laying sets it is usually desirable to concentrate on only one target, so that some form of gated A-scan or B-scan is often used. Where the target is an aircraft, the indicator must be designed to show the altitude as well as the range and bearing.

(4) A third type of application is the use of radar in aircraft interception. In this case the radar indicator must provide enough information for one airplane to be pointed at another, so that the type C-scan, or a modification of it, is used in conjunction with a type B-scan.

b. Methods of ranging. (1) The accuracy with which the range of a target must be obtained varies with the tactical employment of the radar set. For example, range data for fire control must be accurate to within a few yards, while for a reporting station the range data need be accurate only to within 2 or 3 percent of the range. The angular accuracy of the bearing measurement is subject to similar limitations.

(2) Since the range need not be determined with great precision in search radar sets, the sweep is often calibrated by the use of a transparent overlaid scale, as in section III. This enables the operator to estimate the range within the required limits of accuracy. In other

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cases marker pips are used to divide the sweep into equal time intervals to facilitate estimation of the range of echoes.

(3) In applications that require accurate measurement of range, some means is provided for introducing a variable delay to permit aligning the echoes with a reference mark. The reference mark may take the form of a hairline across the face of the oscilloscope or a notch or step in the sweep trace. In some cases the precision of measurement is improved by observing the desired echo on an expanded portion of the sweep.

49. RANGE ESTIMATION

a. Methods of estimation. (1) A given range can be represented by the total length of the sweep on a cathode-ray tube screen. If the transmitted pulse occurs at the beginning of the sweep, the range of a target may be estimated by observing the fraction of the sweep length between the transmitted pulse and the echo. Estimations of this kind depend on the judgment of the operator, and are made less accurate by any nonlinearity of the sweep.

(2) If the radar equipment is installed in a permanent location, there may be a number of fixed targets whose ranges are known. Thus, several points on the sweep may be accurately calibrated, and the ranges of other echoes can be estimated with reference to these known points.

(3) Estimation of range is made somewhat more accurate by the use of range markers which divide the trace into equal time intervals. Markers which appear on the sweep itself, rather than as marks on an overlaid scale, are preferable because they compensate for the effects of nonlinearity.

b. Shock-excited oscillator. (1) A circuit, in which the plate current of a switch tube flows through the inductor of a tank circuit, may be used to produce a damped train of oscillations by cutting off the tube, as explained in section VII, TM 11-466 and Navships 900,016. The frequency stability of this type of oscillation is excellent because the tank circuit is very lightly loaded and the frequency depends in no way on the action of the tube.

(2) One system that is used for generating range markers from the output of a shock-excited oscillator is shown in figure 211. A negative-going square pulse drives the grid of V1 below cut-off at the instant that the sweep starts, thus setting up oscillation in the tank circuit made up of L1 and C2. Sharp, well-defined marker pulses are produced by feeding the output of the tank circuit through the remaining circuits of figure 211. The damped oscillations are limited and amplified by V2 so that the output at the plate is a series of approximate square waves of the same amplitude. Resistor R2

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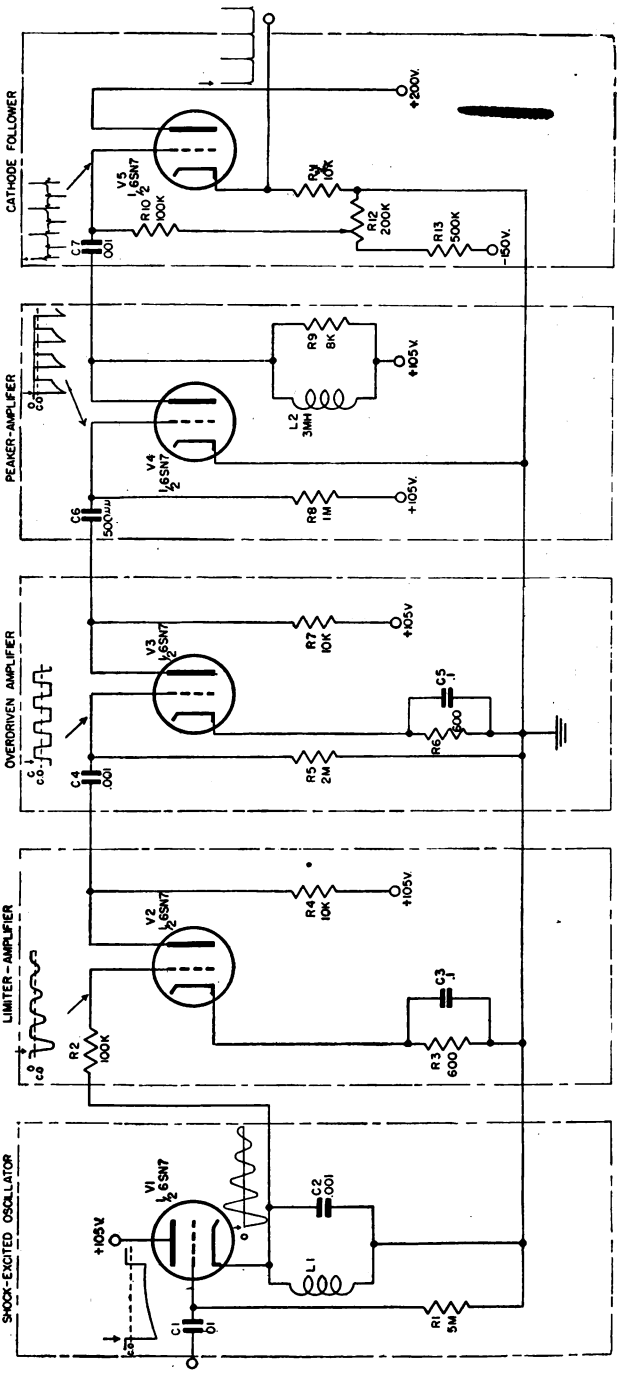

Figure 211. Shock-excited oscillator used for producing range markers.

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in series with the grid limits the grid current and thus reduces any damping effect on the L-C circuit. The cathode bias developed across R3 and C3 prevents the grid from going extremely positive and thus aids in keeping the grid current low. A low-plate voltage is used to aid in the limiting action. The output of V2 is coupled to the grid of V3 which acts as an overdriven amplifier and produces a good square wave at its plate. The peaker-amplifier tube V4 has as its plate load inductor L2 shunted by resistor R9. The inductor resonates with its distributed capacitance at a frequency of the order of 2 megacycles per second. When the tube is cut off by the negative-going square wave the coil is shocked into oscillation. The resistance damps the oscillation almost completely before one cycle is completed so that a positive pulse of approximately 0.25-microsecond duration is produced. When the grid swings positive a negative pulse of smaller amplitude appears at the plate. This has no significance since the following tube is biased below cut-off so that only positive pulses affect its operation. The grid of V4 is returned to a positive potential rather than to ground in order to insure high conduction in the tube just before the grid swings negative. The large resistor, R8, in the grid circuit limits the grid current to a small value. The output of the pulse generator is fed to a cathode follower which is biased below cut-off. By adjusting this bias so that the positive peaks raise the grid above cut-off by the desired amount, the amplitude of the marker pulses can be controlled.

(3) If the oscillations in the cathode circuit of V1 are damped too much to be useful over the entire sweep, a regenerative circuit (fig. 212) can be used to sustain their amplitude. The circuits are identical with those of figure 211, with V6 and V7 added. The sustaining circuit is in the form of a multivibrator with a natural frequency of oscillation much lower than that of the input signal. The output of the L-C circuit is coupled directly to the grid of V6, is amplified in V6 and V7, and fed back to the input point in its original phase, having been inverted twice. The degeneration in the two unbypassed cathode resistors prevents excessive gain which would distort the sinusoidal wave generated in the L-C circuit. The frequency of oscillation is the resonant frequency of L1 C2, while the amplitude is held constant by the action of the multivibrator. When current flows in V1 the oscillations are damped out and start again when the current is cut off. The oscillations are used to generate positive marker pulses as discussed in connection with figure 211.

e. Muitivibrator. (1) Range markers may be generated by the type of multivibrator circuit shown in figure 213. The circuit is turned off and on by a signal applied through C1 to the grid of V1. A negative pulse of relatively short duration cuts off V1 and renders

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the circuit inoperative until the signal goes positive, at which time the sweep also starts. When V1 begins to conduct, its plate voltage drops, and causes the grid of V2 to swing in the negative direction. The current through V2 and consequently the voltage at its cathode decreases. This change, which takes place almost instantaneously, is coupled through C3 to the cathode of V1, driving it in the negative direction. Since the grid of V1 is held at a relatively constant voltage in respect to ground by the charge on C1, the effect of the voltage cou-

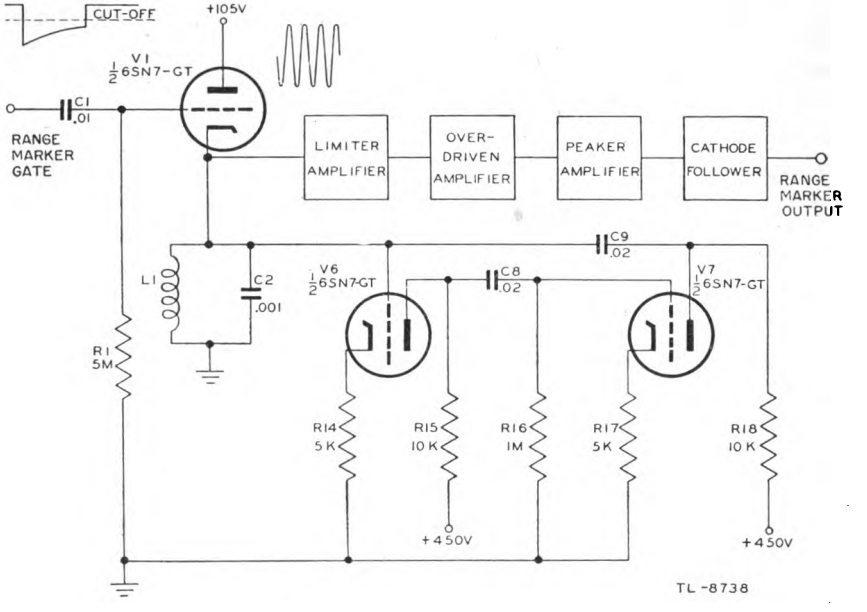

Figure 212. Sustaining multivibrator.

pled through C3 is to increase further the conduction of the tube. This cumulative action cuts off V2 very quickly and drives V1 into saturation.

(2) The plate current of V1 must flow through the three parallel branches in the cathode circuit of the tube. The current that flows in the branches in which there are capacitors causes a change in the charge of the capacitors by withdrawing electrons from one plate of each. This flow of current produces a voltage across the cathode impedance that drives the cathode positive relative to ground. Since the three branches are in parallel, the voltage across each branch must always be the same. The change of voltage that occurs across the branch containing L1 and C2 controls the cathode potential because the rate of change of voltage in this branch is slower than in the others.

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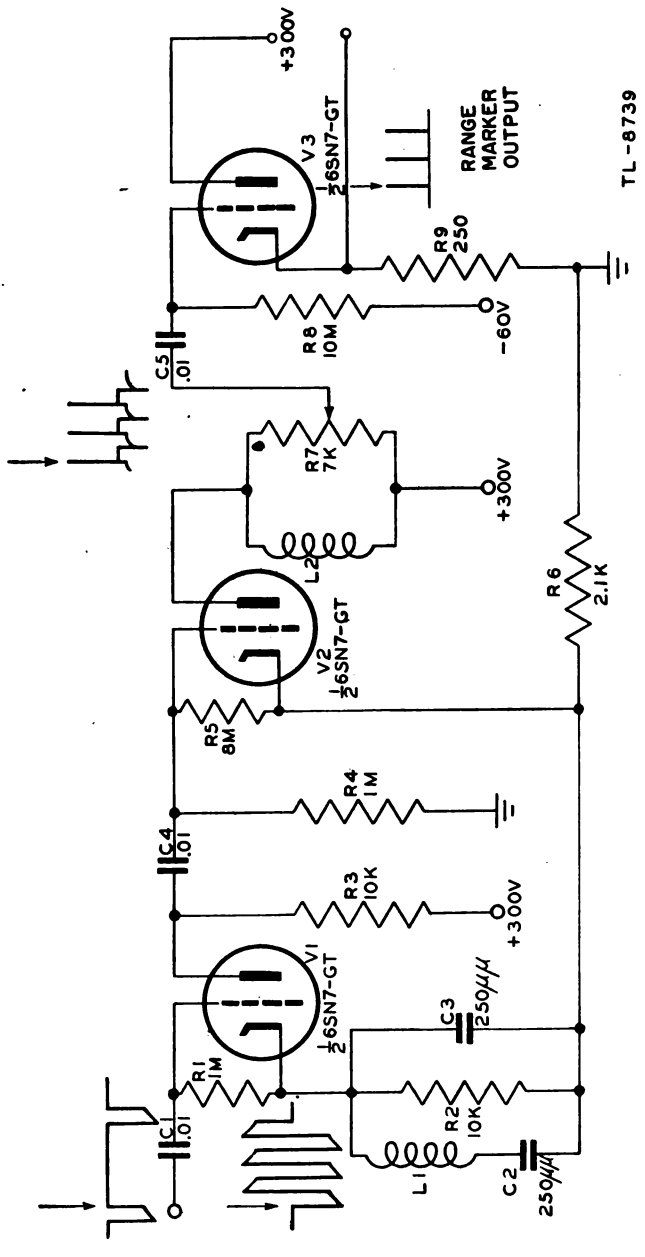

Figure 213. Range marker multivibrator.

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(3) As the voltage rises at the cathode of V1, its current becomes less and its plate voltage rises, causing the voltage at the grid of V2 to rise. When the point is reached at which V2 again conducts, a cumulative effect which is the reverse of that previously described cuts off V1. The tube remains cut off only during the time of one half oscillation of L1 and C2. At the end of this time the voltage across the tank circuit has swung to its maximum negative value, causing the start of a second cycle of the circuit action. Thus, V1 and V2 are made conducting alternately at a frequency determined by the values of L1 and C2. Capacitor C3 is used principally as a means of causing the change from conduction to nonconduction to be abrupt. Resistor R2 is used to damp the oscillatory circuit so that the stopping of oscillation may be controlled by the gate voltage applied to the grid of V1.

(4) Since V2 is cut on and off abruptly, sharp marker pulses can readily be produced in the plate circuit. The action of the plate load impedance is similar to that described in the peaker-amplifier of figure 211. Resistor R7 is a potentiometer which provides a means of controlling the amplitude of the markers. The cathode follower is biased beyond cut-off so that only positive pulses appear in the output.

d. Negative transconductance oscillator. (1) One of the most stable of oscillators used to generate marker pulses is the negative transconductance oscillator, often called the *transitron*. A discussion of the theory of operation of the transition oscillator is given in section V, TM 11-466 and Navships 900,016. Its stability compares favorably with that of a crystal-controlled oscillator with the exception that a steady drift over a long period of time is caused by aging of the oscillator tube. It has the added advantage that its operation can be controlled by a switch tube. A representative circuit for a negative transconductance range-marker system is shown in figure 214.

(2) The plate current of switch tube V1 and the screen current of oscillator tube V2 flow through the inductor in the tank circuit made up of L1, C3, and C4. When the switch tube is cut off, the current in L1 tends to change abruptly, causing the magnetic field around L1 to start to collapse. This collapsing magnetic field induces in the inductor a voltage which drives the screen grid of V2 positive. The voltage induced in L1 sets up in the tank circuit oscillations that are maintained by the action of V2. If the bias on V1 is adjusted to give the proper current through L1, the amplitude of the first cycle of the oscillation in the tank circuit can be made equal to the steady state amplitude. When the switch tube is again made conducting, the tank circuit is effectively shunted by a low resistance and oscillations

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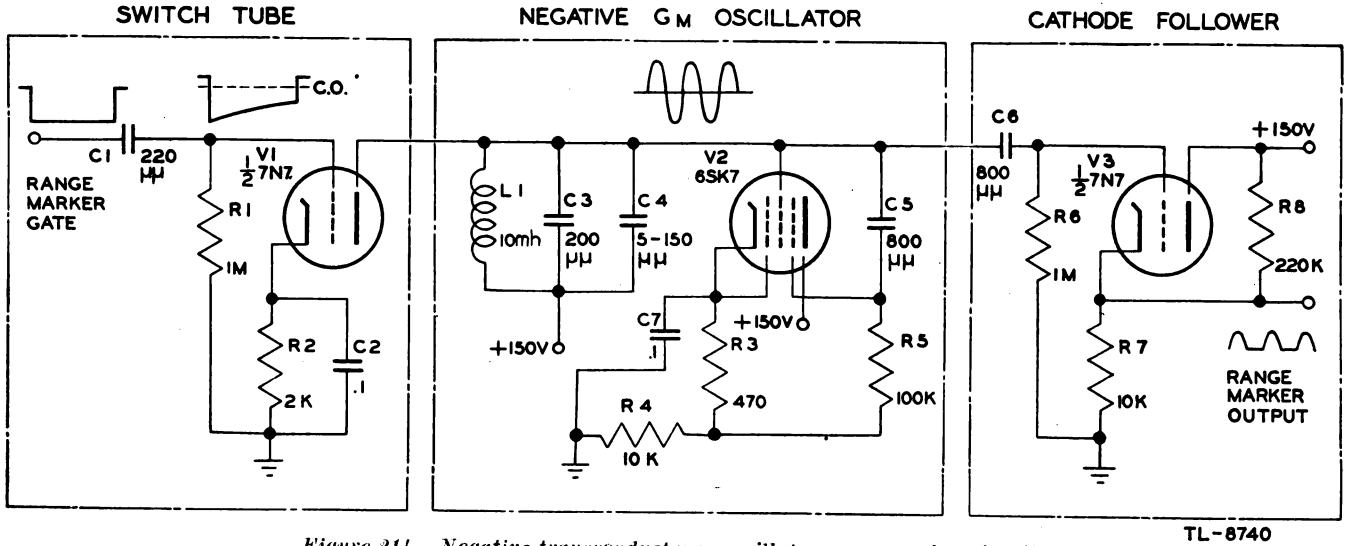

Figure 214. Negative transconductance oscillator range-marker circuit.

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are quickly damped out. Thus, application of a negative gate voltage to the grid of V1 controls the length of time during which oscillations are generated, and insures that the first alternation is always a positive-going half sine wave which starts at the leading edge of the gate voltage.

(3) The output of the transition oscillator is fed into a cathode follower because this type of circuit provides the high impedance necessary to avoid loading the oscillator. Since the cathode follower is biased, the output is a series of half sine waves, which are used as range markers in some applications. The cathode follower in some cases may feed conventional squaring amplifiers and peakers to produce sharp marker pulses.

50. RANGE MEASUREMENT.

a. General. (1) The difficult problem of firing a gun accurately can be simplified considerably if the exact distance between gun and target can be determined. Radar provides a means of finding this distance by measuring the time required for r-f energy to travel out to a target, be reflected, and to return. Precise measurement of range requires the accurate measurement of extremely short time intervals. These intervals are measured by some means of introducing an accurately calibrated variable delay between the transmitted pulse and the echo pulses on the indicator screen.

(2) Several methods of producing a variable delay to measure range are in use in existing radar equipment. One commonly used method is to shift the phase of the sine wave, which times the indicator relative to the sine wave, which times the transmitter. The phase shift is used to delay the action of some circuit in the indicator by a measured number of electrical degrees, and therefore to measure the time in terms of the period of one cycle of the sine wave. The phase-shifting device usually is geared to a dial which is calibrated in yards or other suitable units of range.

(3) The range of a target may also be measured by the use of a circuit which measures the magnitude of the sweep voltage at the position at which the echo pulse appears on the sweep. This method depends on the comparison of the sweep voltage with a calibrated variable d-c voltage, and it is inherently not as accurate as most phase-shifting methods. However, it does find considerable use in search radar sets in which it is desired to measure range to a fair degree of precision.

(4) Other methods of measuring range include the use of a delay multivibrator, an acoustic tank employing a fixed and a movable crystal, and calibrated control of the position of the sweep relative to a fixed marker on the face of the indicator.

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b. Methods of obtaining phase shift. (1) The voltage obtained from a phase shifter should be of constant amplitude at all phases to produce uniform operation of the circuits which follow. In order to make accurate measurements, one degree of rotation of the phase shifter should produce a change in phase of one electrical degree or less. The Helmholtz coil, described in section VII, TM 11-466 and Navships 900,016, is a commonly used device for satisfying these requirements.

(2) Another type of phase shifter using a special capacitor is also satisfactory (fig. 215①). The reactance of capacitor C1 or C2 at the operating frequency of 4.1 kilocycles per second is 4,314 ohms. The resistance of both R1 and R2 is made equal to this value. The current through either R1–C1 or R2–C2 leads the voltage across the transformer secondary by 45°. The voltage across either resistor is in phase with the current and therefore leads the transformer voltage by 45°. The voltage across either capacitor lags the current by 90° and therefore lags the transformer voltage by 45°. If the series impedance of R and C is

$$Z=\sqrt{R^2+X_C^2}$$

and $X_C=R$

Then $Z=\sqrt{R^2+R^2}=R\sqrt{2}$

Therefore, the amplitude of the voltage across a resistor or a capacitor is

$$E_R=E_C=\frac{R}{Z}\times 2E_M=\frac{R}{R\sqrt{2}}\times 2E_M=E_M\sqrt{2}$$

where $2E_M$ is the voltage across the transformer, or E_M is the voltage from M to ground. If E_M is taken as the reference in the vector diagram (fig. 215②), E_R leads E_M by 45°, and E_C lags E_M by 45°. The voltage E_P, measured from P to ground, is the vector difference, E_M-E_{C1}. This difference is found by taking $-E_{C1}$ as a vector equal in magnitude to E_{C1}, but opposite in direction, and completing the parallelogram with E_M. The voltage E_P leads E_M by 90° and has the same amplitude. Likewise the voltage E_N, which is measured from N to ground, is the vector difference E_M-E_R. It is equal in magnitude to E_M and lags E_M by 90°. The voltage E_O, from O to ground, is 180° out of phase with E_M but equal in magnitude since the two points are at opposite ends of a transformer whose center tap is grounded.

(3) Thus, four voltages 90° intervals in phase are supplied to the four stator sections of the phase-shifting capacitor. The rotor plate picks up voltage components from two or three stator sections simultaneously. The voltage at the output is the vector sum of these components. In the position shown in figure 215, the components from plates M and O cancel each other because they are equal in magnitude and 180° out of phase. Consequently the output is 270° out

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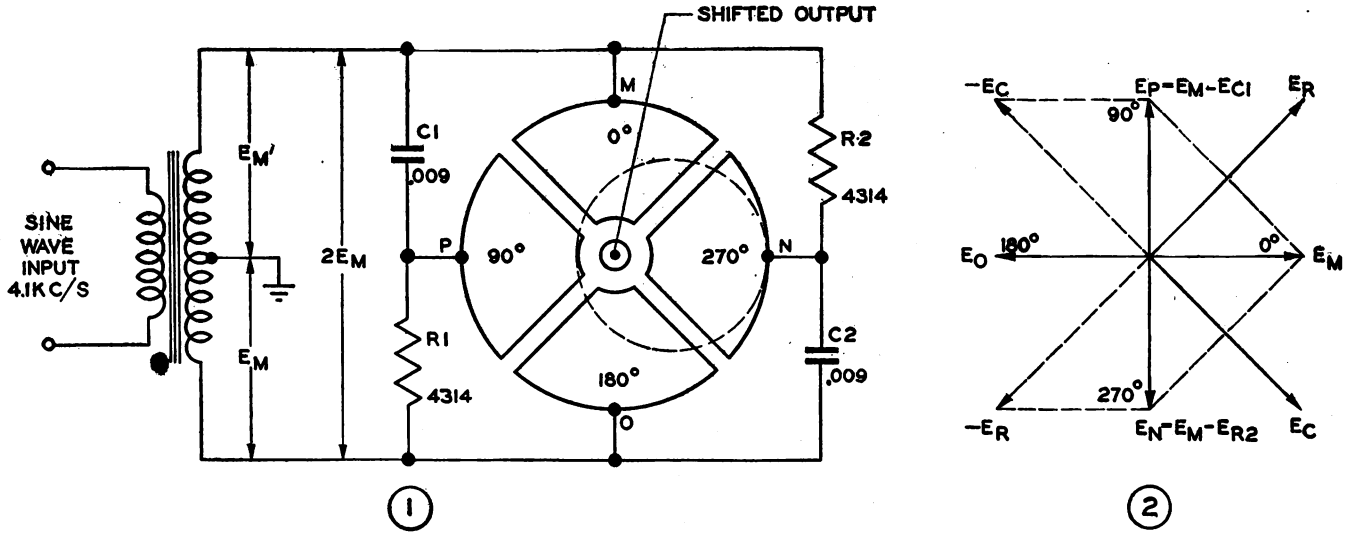

Figure 215. Phase-shifting circuit for producing 360° phase shift.

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of phase with the transformer voltage. The plates are shaped so that the output voltage is of constant amplitude, and that rotation through one degree mechanically changes the output phase one electrical degree.

(4) A modification of this phase shifter uses voltages from the plates and cathodes of two vacuum tubes fed 90° out of phase to supply the excitation for the four stator plates. In addition, a stationary output plate which meshes equally with all stators may be used. The phase shift is then produced by rotating a dielectric plate which varies the capacitive coupling between the output plate and the four energized sections.

(5) The accuracy with which ranges can be measured by phase-shifting methods depends on device used. In extreme cases, the error of the phase shifter may be several electrical degrees. The time error resulting from inaccurate phase shifting may be reduced by making the frequency of the sine wave high so that one electrical degree represents an extremely short time. This requires a means of counting or selecting cycles as well as a means of producing an accurate phase shift.

c. Generation of fixed range marker by phase shift. (1) In many applications the phase shift is used to control the starting time of the sweep, so that as the phase of the timing voltage to the indicator is changed the transmitted pulse and echoes appear to move along the sweep. Some marker at a fixed position on the sweep is used as a reference. The marker may be a hairline on the face of the cathode-ray tube, or a step or notch generated at a fixed time after the beginning of the sweep.

(2) In figure 216② the timing sine wave to the transmitter and the phase of the transmitted pulse and an echo relative to this sine wave are shown. If the phase shifter is set to zero range, the phase of the indicator timing sine wave and the phase of the sweep voltage relative to the transmitted pulse are as shown in figure 216①. The indicator is designed so that a hairline on the screen always appears in the middle of the sweep trace. Thus, the appearance of the indicator screen at zero range is shown in figure 216④. However, if it is desired to find the range of an echo, the phase of the indicator timing sine wave must be changed so that the sweep starts before the transmitted pulse is sent out. Thus, if the indicator timing voltage is made to lead the transmitter timing voltage by the amount shown in figure 216③, the echo will appear at the reference hairline as in figure 216⑤. Note that the transmitted pulse and echo have moved across the screen but that the sweep still occupies the same space on the screen.

(3) Some radar equipments use a phase shift of two different frequencies to improve the accuracy of range measurement. The master

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oscillator of the timer in such a system generates a sine wave which is applied to a phase shifter to time the indicator, and from which a modulation pulse is generated to operate the transmitter. A highly selective filter selects a voltage of one of the harmonic frequencies of which the pulse is composed, and this voltage is also fed to the indicator through a phase shifter. If the 18th harmonic is selected, one cycle of the harmonic is equal in time to 20 electrical degrees of the repetition frequency. The two phase shifters must be geared in an 18-to-1

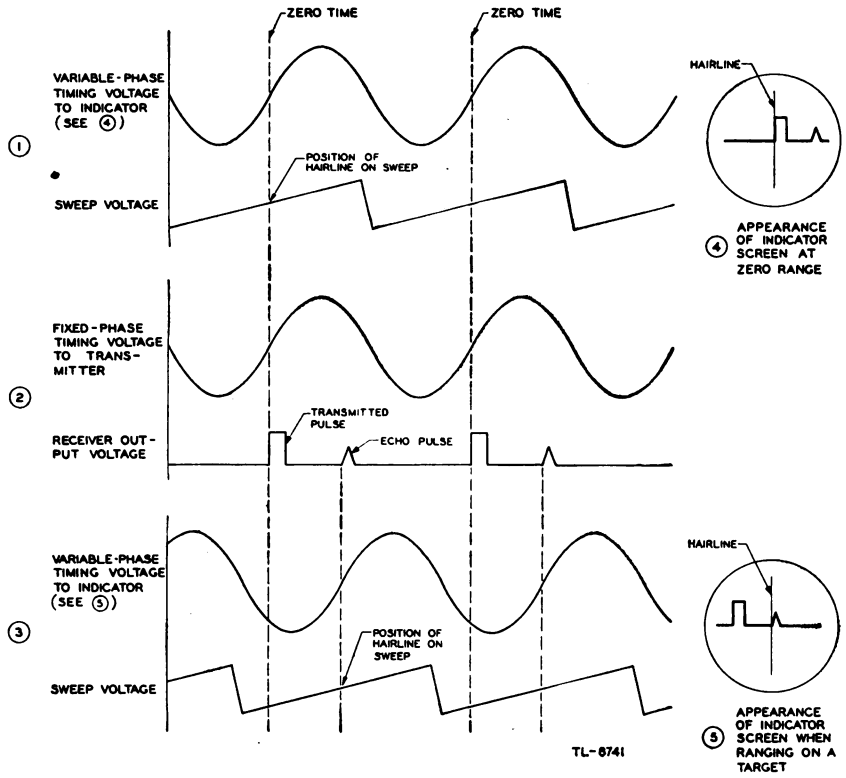

Figure 216. Sweep timed by phase shift.

ratio so that the shift at the harmonic frequency is 18 times as great as that at the fundamental, in order to measure the same time interval. In the circuits following the phase shifters the fundamental voltage is squared and peaked; the harmonic voltage is limited, amplified, and differentiated until only narrow peaks appear. The peaking circuit of the fundamental is a push-pull arrangement whereby two peaked-voltage wave forms, one the inverse of the other, are obtained.

(4) A circuit, which uses these voltages to produce both a sweep trigger and a reference marker notch whose phase is always such that it appears in the center of the sweep, is shown in figure 217. The peaks

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of the harmonic frequency are applied to the grid of V1, and the peaked waveforms of the fundamental frequency are produced by the short time constant R-C circuit consisting of R2 C2 and R3 C3. The resistors R4 and R5 in series with the grids of V2 and V3 limit the swing of the grids in the positive direction. The duration of the peaks from the fundamental is such that one and only one of the peaks of the harmonic frequency can occur during this time. At the time indicated by the arrows on the wave forms the current in V2 is reduced greatly while that in V3 is increased slightly. The total current

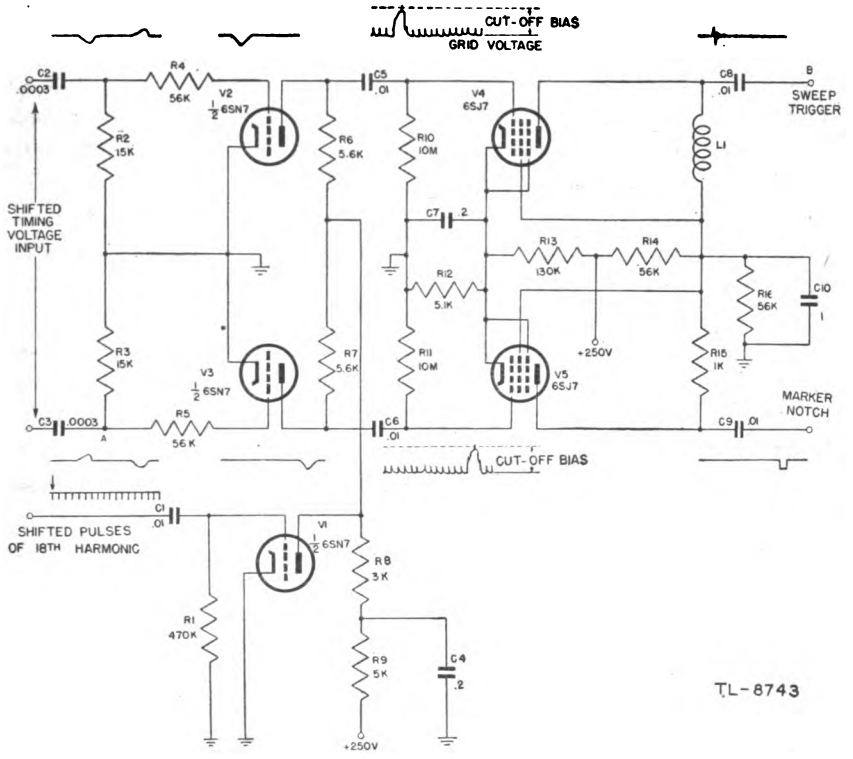

Figure 217. Circuit for producing fixed-phase reference notch.

through the two tubes and therefore the voltage drop across R8 are reduced. The voltage drop across R6 is reduced, while that across R7 is increased. The two effects in R6 and R8 are in the same direction and therefore add, while in R7 and R8 they are opposite and tend to cancel each other. The result is a definite positive pulse at the plate of V2 and perhaps a slightly positive pulse at the plate of V3. The reduced current in V1, caused by the negative pulses on its grid, flows through R8 and produces positive pulses at the plates of both V2 and V3 so that the fundamental and harmonic voltages are mixed. When the polarity of the pulses on the grids of V2 and V3 is reversed

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a half cycle of the repetition frequency later, the previously described action of the tubes is reversed. The resulting wave form at each plate is a series of pulses recurring at the rate of the harmonic frequency with every 18th pulse on top of a pedestal. The two pedestal voltages are 180° out of phase with each other, since one occurs at the positive peak and the other at the negative peak of the fundamental sine wave.

(5) Note that the time constant of the coupling circuits into V4 and V5 is extremely long. The grid leak bias produced in these coupling circuits, combined with the cathode bias produced across C7 and R12, permits only the pulses which are on the pedestals to cause conduction. The plate load of V4 is an inductor which is shocked into oscillation with its distributed capacitance when the tube is suddenly made conducting. The inductor is used because a positive trigger pulse is required for the thyratron sweep generator which follows. The positive pulse is obtained from the second swing of the oscillation, so that the use of a phase inverter tube is avoided. The slight delay introduced by this method is compensated for in the zero adjustment of the phase shifter. The output of V5 is a negative notch voltage which is applied to a vertical deflecting plate of a cathode-ray tube as a marker. Since the marker is always generated one half cycle of the fundamental after the generation of the sweep trigger, it appears stationary on the screen as the phase of the sine-wave timing voltage is changed.

d. Generation of movable range marker by phase shift. (1) In some methods of measuring range a marker is produced which is moved along the sweep to the position of the echo whose range is desired. The control which causes this motion is calibrated directly in yards so that the range may be read from the setting of the control. Where a phase-shifting method is used to produce the marker, the transmitted pulse and the sweep are timed from the same sine wave. The phase of these voltages relative to the timing sine wave is shown in figure 218①. The timing sine wave is also applied through a phase shifter to a range-mark generator. The range mark, shown as a notch in figure 218, is generated at some fixed phase of the phase-shifter output in figure 218②. When the phase shifter is adjusted to the zero-range position, the notch voltage has the phase relative to the sweep shown in figure 218②, producing a picture on the indicator screen like that in figure 218④. When it is desired to range on a target, the phase of the voltage to the notch generator is shifted as in figure 218③ so that the notch moves along the sweep to the position of the echo. When the echo is centered in the notch, as in figure 218⑤, the range may be read from the calibrated dial.

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(2) In many radar systems the timer does not produce a sine wave. However, advantage may be taken of the accuracy of range measurement possible with phase-shifting methods by using the circuit shown in block form in figure 219①. The timing pulse from the transmitter (fig. 219②*A*) controls the operation of a one-shot multivibrator which produces a square-wave output, *B*. During the negative portion of this square wave a timing wave, *C*, is generated by a shock-

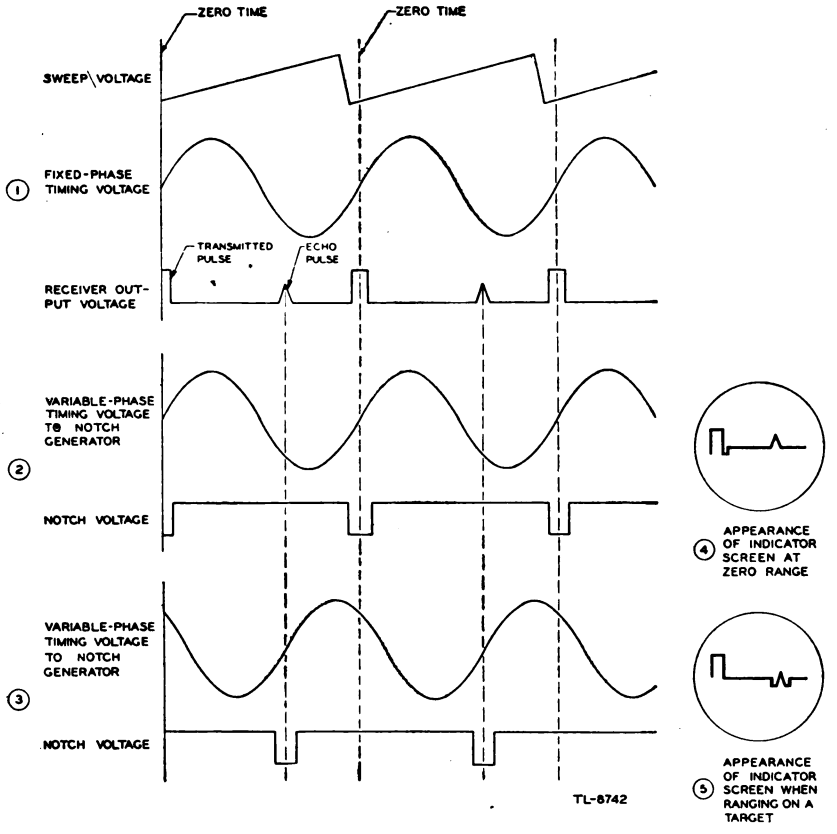

Figure 218. Movable marker timed by phase shift.

excited oscillator, tuned to 81.955 kilocycles per second. This sine wave is applied to a phase shifter of the type described in b above. The shifted output, *D*, is amplified and differentiated to form a train of sharp positive and negative pulses *F*. These pulses are combined with a sawtooth voltage in a pulse-selector circuit, *G*. By varying the cathode potential in this circuit the cut-off point may be shifted to select any of the positive pulses to produce a single output marker, *H*.

(3) The schematic circuit diagram of the pulse selector is shown in figure 220. The voltage drop across V1 is very small in the absence

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of an applied signal because the grid is connected through R1 to $B+$. The negative swing of the one-shot multivibrator cuts off V1 for the duration of the sweep, allowing capacitors C3 and C4 to charge through R2 and R3 toward +300 volts. The timing pulses produce

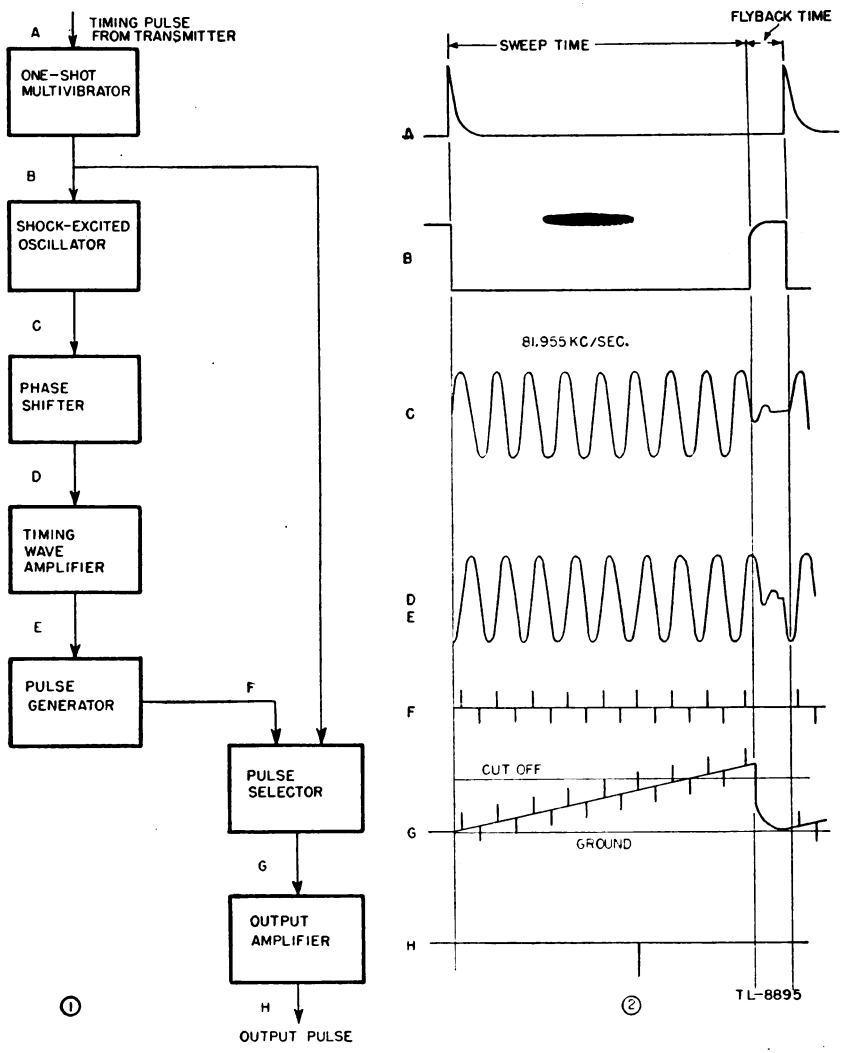

Figure 219. Block diagram of method of producing movable range mark by phase shift.

a voltage across R3 which is in series with the sawtooth voltage developed across the capacitors, so that the sum of these two voltages appears at the grid of V2. The bias on this tube is controlled by potentiometer R6 so that V2 cannot conduct until the grid voltage

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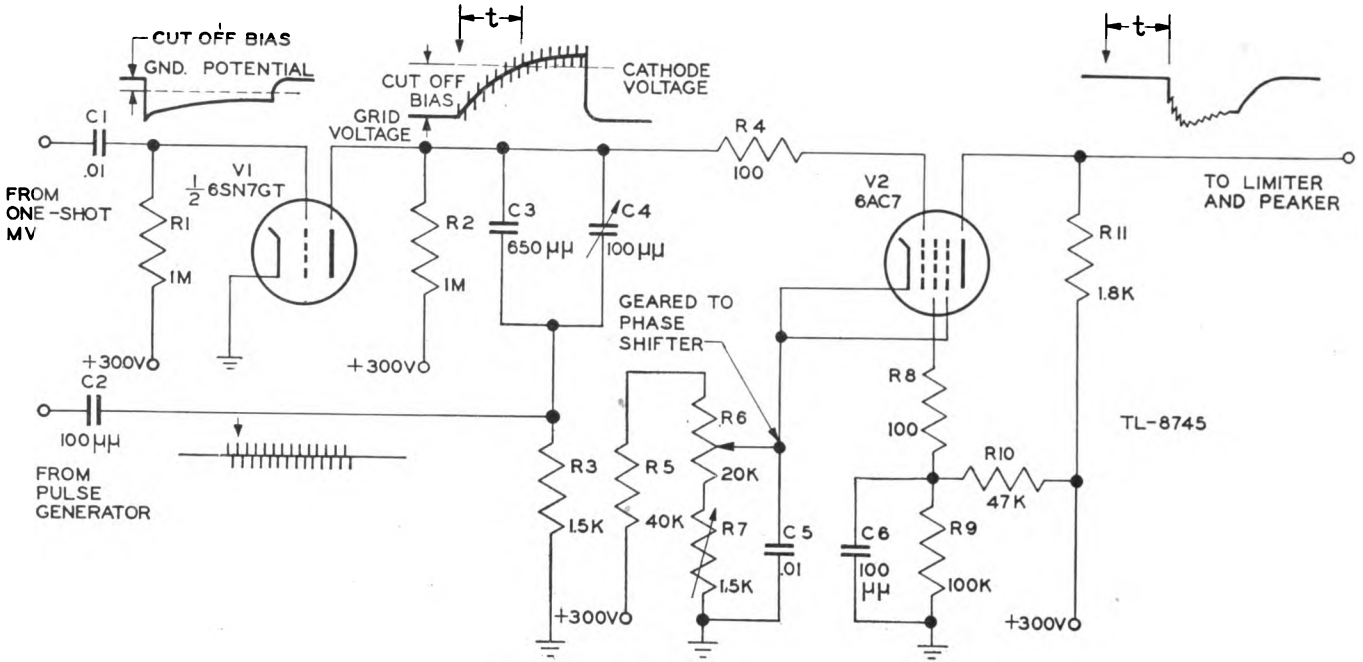

Figure 220. Schematic circuit diagram of pulse selector.

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rises above cut-off. The first timing pulse which drives the grid above cut-off causes a sharp drop in voltage to take place at the plate of V2. If only R6 is varied, tube V2 will be made to conduct at intervals corresponding to 2,000 yards of range because the frequency of the timing voltage was made 81.955 kilocycles per second. However, since the phase of the timing voltage is varied, a smooth variation in the time at which V2 begins to conduct can be obtained if potentiometer R6 is geared to the phase shifter, while the phase is changed so that the pulse one step farther up or down the slope causes conduction. The range marker is generated at the time that V2 first conducts. Thus the combination of phase shifter and potentiometer measures the interval between the transmitted pulse and the marker. The accuracy of this measurement is improved by taper-

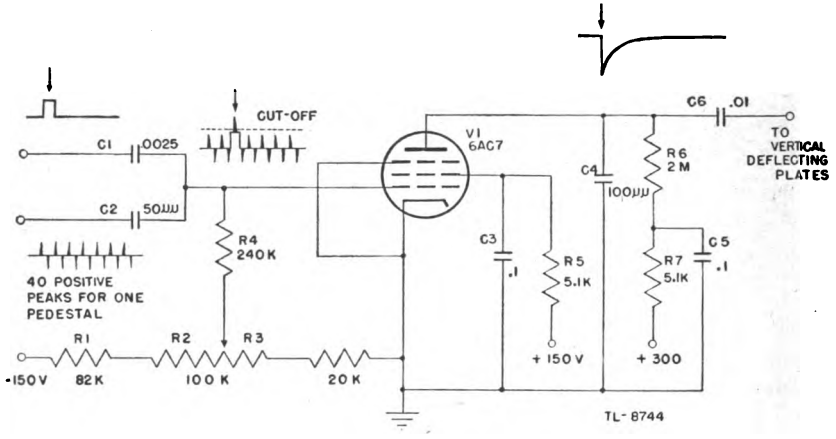

Figure 221. Circuit for producing movable range marker by phase shift.

ing potentiometer R6 to compensate for the nonlinearity of the sawtooth voltage generated by V1.

(4) The type of circuit discussed in c above may be adapted to the generation of a movable range marker by the use of the circuit shown in figure 221. The timing sine wave for the radar system and the fortieth harmonic of the timing frequency are each fed to phase shifters which are geared together in a 40-to-1 ratio. The fundamental is used to produce a pedestal voltage and the harmonic voltage is converted into a series of sharp positive and negative pulses. These voltages are capacitively coupled to the grid of a tube which is biased so that only the pulse on the pedestal can cause conduction. Capacitor C4 is discharged through V1 during the time that the pulse makes the tube conduct. After the pulse passes, C4 charges again to +300 volts through R6. The wave form produced is in the form of a step which is applied to a vertical deflecting plate as a range marker

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(fig. 223). The height of the step may be controlled by adjusting the bias on V1 to vary the effective resistance of the tube during the conducting time. The sweep is always started at the time of the transmitted pulse, so that the step moves as the phase shifters are turned.

e. Generation of movable range marker from sweep voltage. (1) A circuit which uses the sweep voltage to produce a time delay for the generation of a range marker is shown in figure 222. The sweep voltage shown in figure 222Ⓐ is coupled directly from the sweep generator to the grid of V1. This tube is operated as a biased cathode follower, the bias being supplied by the voltage divider consisting of R2, R3, and R4. The bias is adjusted by means of R3 to cause the tube to begin conducting at any instant from the beginning to the end of the sweep. The duration of the sweep is indicated as "*S*" in the wave forms and the variable interval between the start of the sweep and the start of conduction in V1 is shown as "*t*."

(2) The voltage at the cathode of V1 (fig. 222Ⓑ) remains constant at the level selected by delay control R3 until the instant when the sweep voltage drives the grid more positive than cut-off. At this time the cathode voltage begins to rise at the same rate as the sweep voltage. The cathode voltage is coupled out through C2 and R5 to a differentiating circuit consisting principally of C3 and R6. The linear rise of voltage that takes place starting at time *t* (fig. 222Ⓒ) causes a sudden rise of voltage (d) in the output of the differentiating circuit. This sudden rise is amplified by V2 and the resulting wave form Ⓔ is applied to a vertical deflecting plate of a cathode-ray tube to serve as a range marker. The indicator screen has the appearance shown in figure 223①. The range is measured by varying R3 until the step coincides with the left-hand edge of the desired echo. The shaft of R3 is geared to an indicator on which the range is shown in yards or miles.

(3) The accuracy of the delay control may be checked by applying to the sweep range markers such as those discussed in paragraph 50d. After the speed of the sweep is adjusted to the proper value, the delay control may be adjusted by variation of R2 and R4 to compensate for slight nonlinearity of the sweep.

f. Generation of movable range marker by delay multivibrator. A one-shot multivibrator which can be used to provide a variable delay for the measurement of range is shown in figure 224. The operation of the circuit is very similar to that described in paragraph 26b. In the resting state V1 is conducting, while V2 is cut off by the bias provided by the voltage divider made up of R3 and R4. Since the grid of V1 is returned to the plate of

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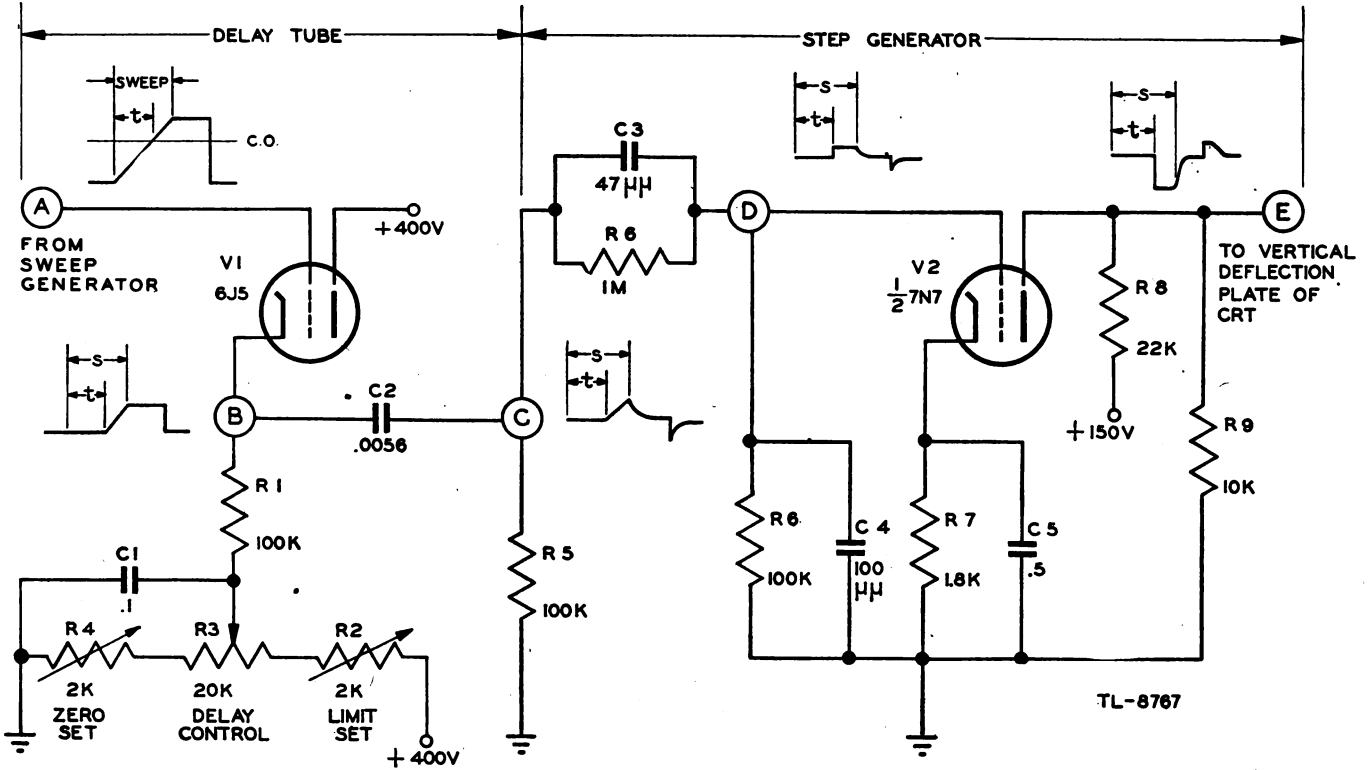

Figure 222. Circuit for generation of movable range marker from sweep voltage.

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V2, it tends to be positive. A charge on C2, resulting from grid current, holds the grid of V1 essentially at ground potential, and the grid current of this tube is limited to an average value of less than half a milliampere by resistors R2 and R6. A negative pulse, generated at the time of the transmitted pulse, is applied through C1

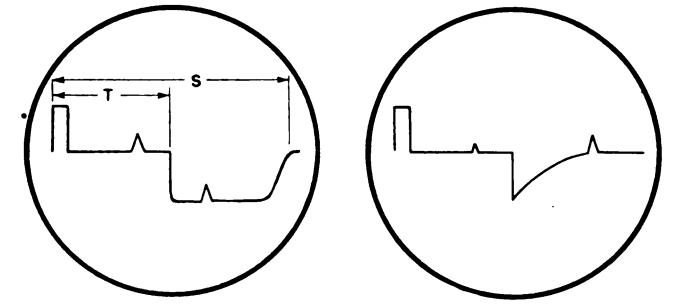

Figure 223. Range marker steps.

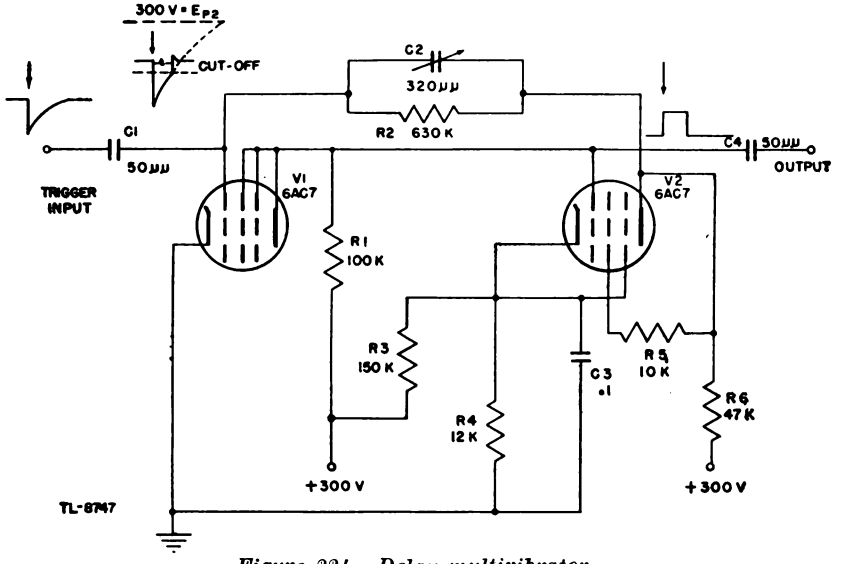

Figure 224. Delay multivibrator.

to the grid of V1. The multivibrator action causes V2 to conduct and drives the grid of V1 below cut-off, and the charge on C2 begins immediately to leak off through R2. As a result of this leakage the potential at the grid of V1 returns toward that at the plate of V2 at an expotential rate which depends on the time constant R2 C2. When the potential at the grid reaches such a value that V1 again conducts,

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V2 is cut off, C2 is charged quickly to its normal voltage by grid current, and the circuit is returned to its normal resting state until another negative pulse is applied. The output, a positive pulse taken from the plate of V1, is differentiated, and the pulse from the trailing edge is used as a range marker. Thus a time delay, equal to the width in microseconds of the pulse from the multivibrator, is produced. The width of this pulse is controlled by varying C2. The control is made more accurate by returning the grid of V1 to a positive potential rather than to ground, causing the grid-potential curve to have a steeper slope at its point of intersection with the cut-off line. The shaft of C2 is geared to a dial calibrated to indicate range.

51. A-SCAN MODIFICATIONS.

a. Gated sweep. A sweep is said to be gated if its duration as well as its starting time is controlled by a voltage applied to the sweep generator. A similar voltage is usually applied to the cathode-ray tube to intensify the screen for only the duration of the sweep. Thus echoes which return before or after the application of the gate voltage do not appear on the screen. In some cases the gate pulse begins at the time of the transmitted pulse and is made sufficiently wide to cover the desired range. In other cases the gate is designed to select only a small part of the total range so that undesired echoes may be excluded from the indicator screen.

b. Expanded sweep. (1) A portion of the range sweep in the vicinity of the range marker is sometimes expanded to facilitate accurate ranging. This result is accomplished by increasing the speed of the sweep of the electron beam across the screen for a part of the time. A circuit which is used in conjunction with the circuit of figure 217 to produce a fast sweep near the range markers is shown in figure 225.

(2) The linear sweep is generated by charging capacitors C5 and C6 through R5 and discharging them through thyratron V1. The timing of the discharge is controlled by the oscillatory trigger pulse applied to the grid of the thyratron. The positive pulse which is applied to the grid of V2 occurs at the same time that the marker notch was generated in figure 217. The width of the notch is equal to the width of the small pulse on top of the pedestal. Therefore the leading edge of the pedestal voltage applied to the sweep-expansion generator occurs a few microseconds before the marker and the trailing edge a few microseconds after it.

(3) Tube V2, which is normally cut off by the bias provided by the voltage divider consisting of R13 and R14, is made to conduct by the application of the pedestal voltage. Capacitors C11 and C12 discharge through the tube at a rapid rate during a time equal to the

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width of the pedestal. When V2 is not conducting, the capacitors charge at a relatively slow rate through R15. The resulting wave form is amplified and inverted in V3. The output of the sweep expansion generator is combined in series with the output of the gas tube sweep generator in the resistance network made up of R8, R9, and R10. The resultant voltage is the algebraic sum of the two sawtooth voltages. Application of this sweep voltage to the horizontal deflection plates of a cathode-ray oscilloscope produces a pattern on the indicator screen

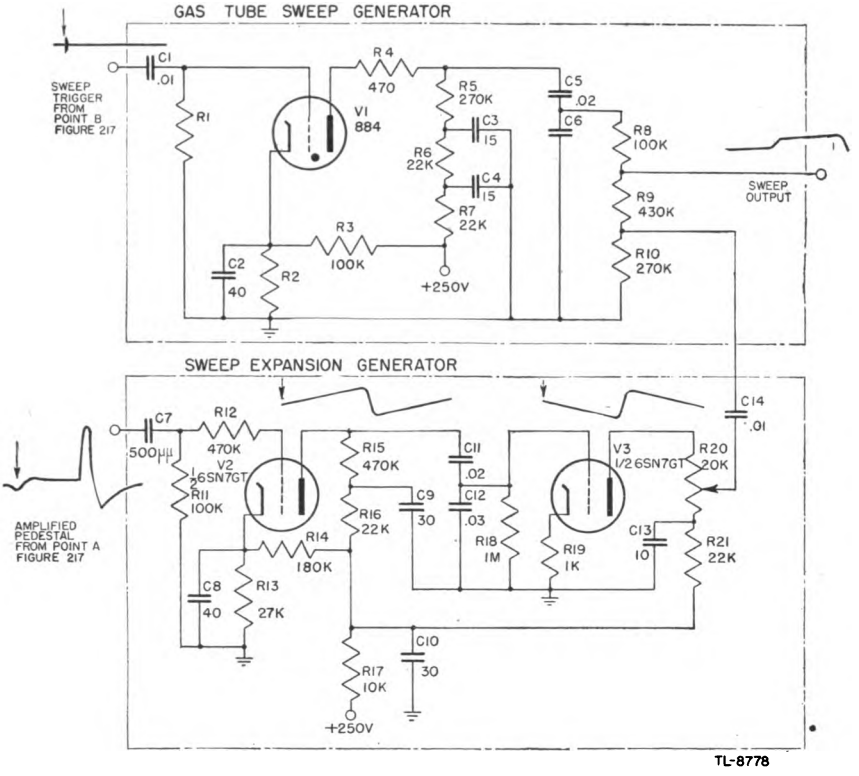

Figure 225. Circuit for producing sweep expansion in vicinity of fixed range marker.

like that shown in figure 226. Note that the sweep speed is fast on each side of the range marker, as may be seen from the relative widths of the echo pulses shown, and that the trace is wider and brighter where the sweep speed is normal.

(4) The sweep may be expanded in the vicinity of a movable range marker by the use of a circuit like that shown in figure 227. Tube V1 is normally at zero bias and therefore holds the charge on Cg at a constant high level. When V1 is cut off by the negative sweep gate voltage applied to the grid, C6 discharges through V2 at an essentially

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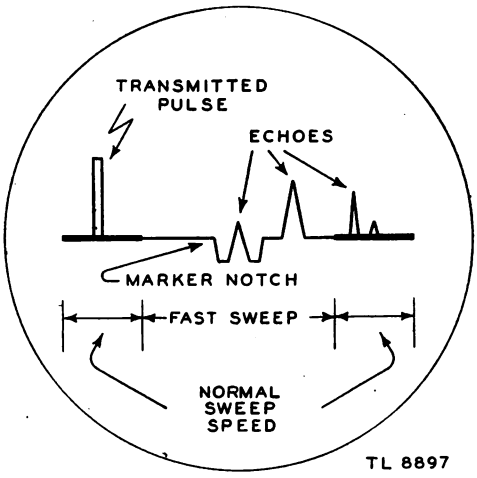

Figure 226. Sweep expanded in vicinity of range marker.

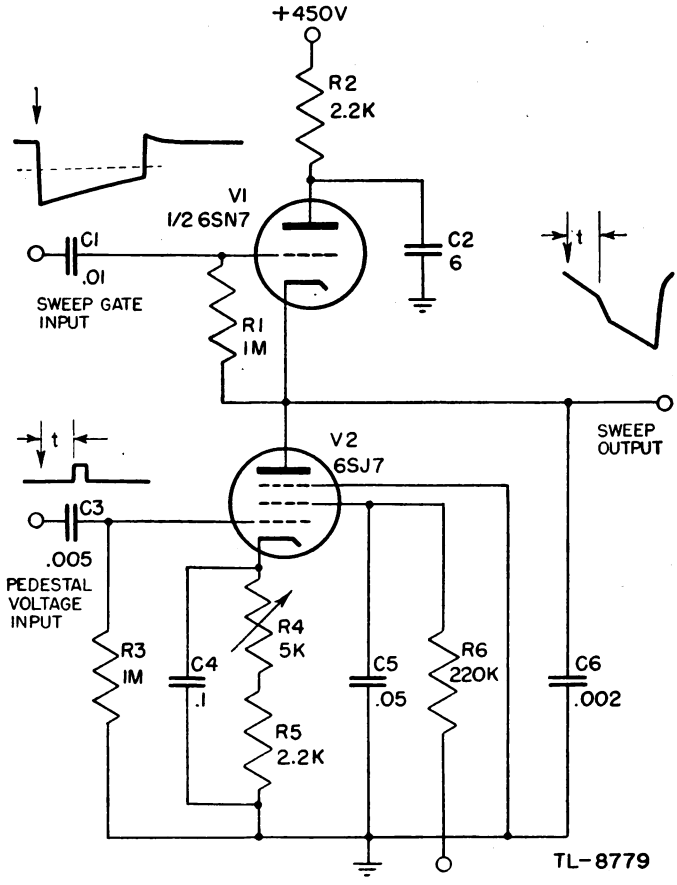

Figure 227. Circuit for producing sweep expansion in vicinity of movable range marker.

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constant rate, producing a linear decrease of voltage at the plate of the tube. When a positive pedestal signal such as that used in figure 221 is applied to the grid of V2, the rate of discharge of C6 is increased for the duration of the pedestal. At the end of the pedestal the discharge rate returns to its original value for the duration of the sweep.

c. Precision sweep. A form of expanded sweep which is gated so that any small portion of the whole range is made to occupy the full width of the indicator screen is termed a precision sweep. Such a sweep may be used with the range-measuring method shown in figure 221. The sine wave from which the pedestal is generated is greatly amplified and applied to a double diode limiter to produce the wave form shown in figure 228①.

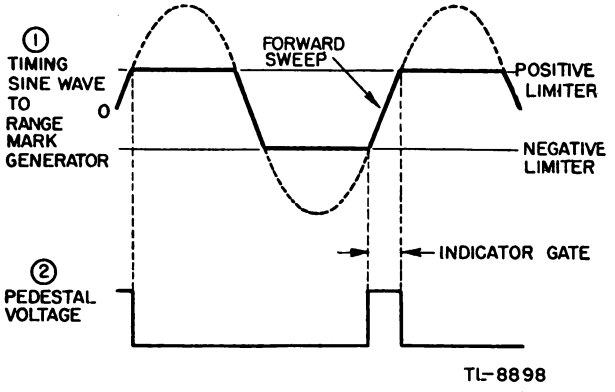

Figure 228. Production of precision sweep.

The portion of the sine wave between the limits is nearly linear, and it is used as the sweep. The pedestal generating circuit and the sine-wave amplifier are phased so that the step always appears at the center of the precision sweep, and so that the pedestal voltage occurs during the rising portion of the limited sine wave. The amplification of the sine wave is such that the precision sweep trace corresponds to approximately 2,000 yards of range. Thus, under control of the phase shifter, any 2,000-yard portion of the range can be examined carefully and the range of the target accurately determined.

52. B-SCAN.

a. General. It has been indicated in section II that the type B-scan oscilloscope indicates range and azimuth. Usually a cathode-ray tube with magnetic deflection and a long persistence screen is used, and the tube is intensity-modulated by the signal voltage to cause the position of the target to be indicated by a bright spot on the screen. The scan covers a rectangular area on the screen, with the range shown

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vertically and the azimuth horizontally. Clamping may be used on the signal voltage so that the instantaneous potential at the grid of the cathode-ray tube depends only on the signal amplitude and not on its waveform.

b. Azimuth sweep. The scanning in azimuth is at a relatively slow rate—one sweep across the tube for each revolution in azimuth of the antenna. Therefore the sweep current can be controlled by a potentiometer mounted on the shaft which rotates the antenna (fig. 229). If contactors *A* and *B* of the potentiometer are at the same potential, no current flows through the horizontal deflecting coil. If the

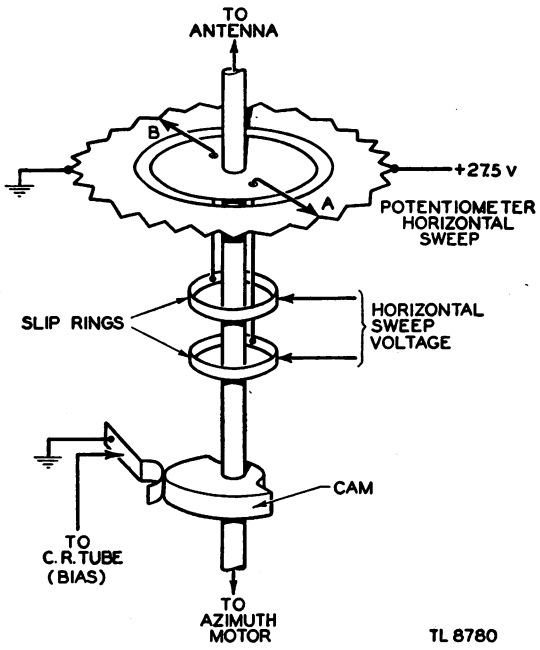

Figure 229. Sweep potentiometer.

potential at *A* is higher than that at *B*, current flows and the beam is deflected. The maximum deflection to the right occurs when *A* is at the point of application of the positive voltage and *B* is at ground. If the positions of *A* and *B* are reversed, the current flow and the deflection of the beam are in the reverse direction. The same voltage ranges are covered whether the antenna is pointing forward or backward. Therefore a cam-operated switch is used to prevent signals received from the rear from appearing on the indicator.

c. Range sweep. (1) A sawtooth voltage, which is generated in a manner similar to the generation of an A-scan sweep, is used to produce a range sweep by causing a linear rise of current in the deflecting coils (fig. 230). This sawtooth voltage is coupled through C1

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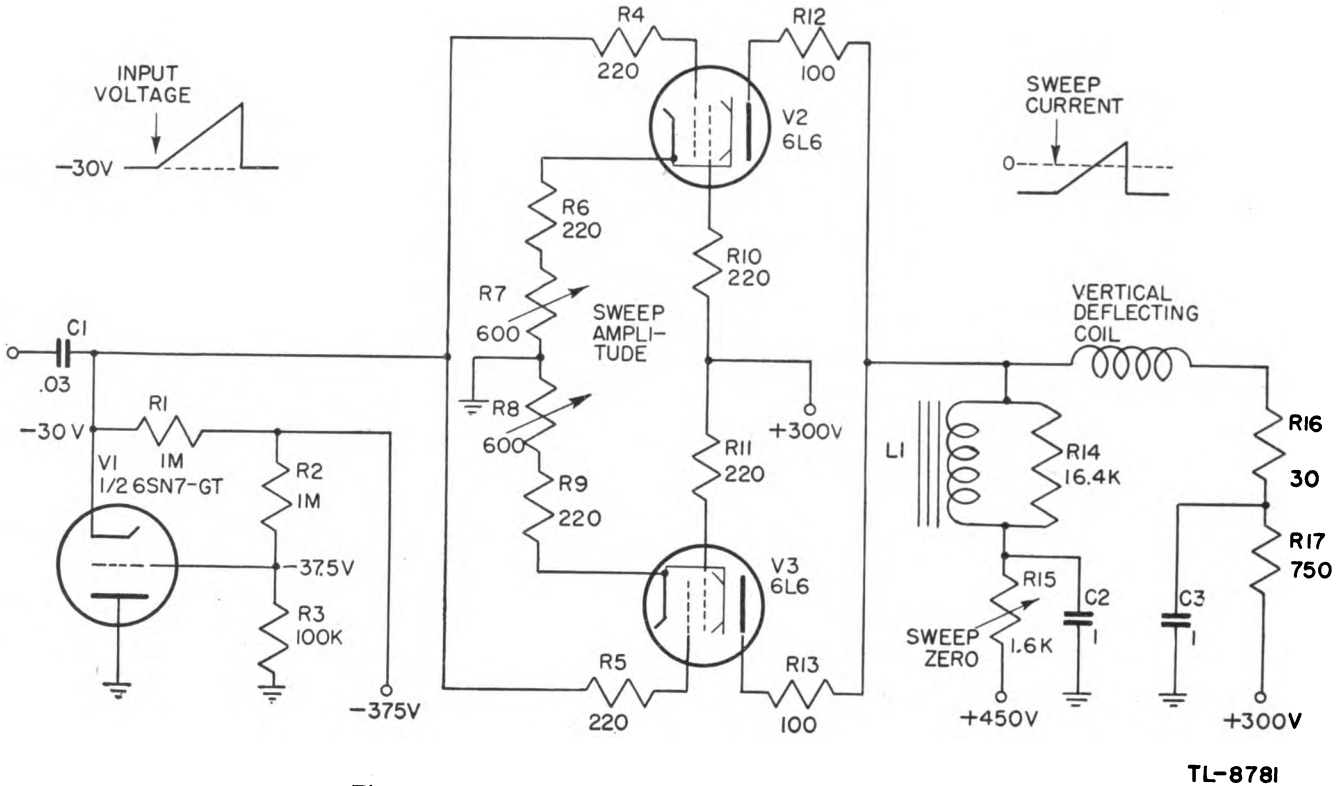

Figure 230. Range sweep generator for magnetic deflection.

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to the grids of V2 and V3 which are operated in parallel. The clamping action of V1 (sec. VII, TM 11–466 and Navships 900,016) insures that the potential at the grids of these tubes is at the same level at the beginning of each sweep. Both tubes are biased near cut-off so that the plate current is small in the absence of a signal on the grids. This small current flows through L1, R14, and R15 to the 450-volt source. At the same time a current flows from the 300-volt source through the vertical deflecting coil to the 450-volt source. The magnetic field set up by this current deflects the electron beam toward the bottom of the indicator screen. The range sweep is made to start from the zero reference line by adjustment of R15 which controls the magnitude of this current.

(2) When the positive sawtooth voltage is applied to the grids of V2 and V3, the current in the tubes starts to rise rapidly. The inductance of L1 is sufficiently large to prevent the 450-volt source from supplying the added current. Therefore the current is supplied by the 300-volt source, and the current through the deflecting coil begins to fall to zero and to build up in the opposite direction. Thus a current, which rises from a negative value to an equal positive value in proportion to the applied sawtooth voltage, is produced in the deflecting coil.

53. C-SCAN.

a. General. The type C-scan presents the azimuth angle horizontally and the elevation angle vertically. Its chief applications are for aircraft interception and beam landing. The grid is intensity-modulated by the signal. The rate of covering an area may be 15 to 20 times in azimuth for once in elevation. It is desirable to have a fairly large number of sweeps in one direction for one in the other in order to get good coverage of the area which is being scanned. The circuit for the azimuth sweep is essentially the same as that for the type B-scan.

b. Elevation sweep. Since the elevation sweep is even slower than the azimuth, a potentiometer is used for this sweep also. An electrical circuit identical with that for the azimuth may be used. The potentiometer is driven by the rotation of the antenna in elevation. The angular coverage in elevation may be approximately 70° as compared to 180° in azimuth, which makes possible the use of gears that drive the elevation potentiometer arm through as much as 2.5° for every degree of rotation of the antenna. Without gears only a small portion of the available voltage would be developed across the contact arms, because of the limited motion. By the use of gears, practically all of the voltage can be used to produce a more accurate control of the vertical position of the spot on the indicator screen.

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c. Range gate. Because the motion of the beam is slow, the length of the line scanned during the pulse-repetition period is very short. All signals or noise which reach the screen during this whole interval tend to pile up, essentially at a point. The desired signal cannot be distinguished from the noise unless the signal-to-noise ratio at the receiver output is very good. Most of the noise or undesired signals can be eliminated by gating the cathode-ray tube, if the range of the target is known. The gate voltage should be a pulse with a time duration that is a small portion of a pulse-repetition period, and a starting time that is controlled by range-measuring device. For example a pulse which is used to produce an expanded sweep, as discussed in paragraph 51b, may serve as a gating pulse. Only the signals and noise which appear at the grid of the cathode-ray tube during the time of the pulse are permitted to reach the screen. Thus the effect of noises produced during the remainder of the pulse repetition period is nullified and the target is distinguished more readily.

54. PPI-SCAN.

a. General. The PPI-scan is similar to the B-scan in that it indicates range and azimuth. The range sweep starts at the center of the screen and moves outward along a radius in a direction corresponding to the direction in azimuth of the radiated beam. The cathode-ray tube is of the magnetic deflection type with a long-persistence screen. The range sweep is made linear so that range is indicated by the distance from the center of the screen of the spot produced by an echo. A deflecting yoke which is made to rotate in synchronism with the rotation in azimuth of the antenna may be used to rotate the range sweep in step with the antenna. Since the grid is intensity-modulated by the received signals, a polar map of the surrounding territory is produced on the screen if the beam is directed in the plane of the horizon.

b. Selsyn sweep. (1) Most PPI indicators use a pair of deflecting coils which are rotated around the cathode-ray tube to produce a rotating sweep, as in section IV. However, if it is desired to avoid the mechanical difficulties involved in this system, the sweep may be rotated by the electrical means shown in figure 231. Transformer T1 is a special selsyn transformer of which the rotor, or primary, is turned mechanically as the antenna is rotated in azimuth. Two stator, or secondary, windings are placed at right angles to each other. As a result the amplitudes of the induced voltages vary sinusoidally with the rotation of the primary, and the position of the rotor which causes the voltage in stator I to be a maximum is 90° away from the position which induces maximum voltage in stator II. Although the alterna-

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tions of the voltages induced in the stators are always in phase, the variations of the amplitudes are effectively 90° out of phase because of the 90° separation of the stator windings. Since the output of stator I controls horizontal deflection and the output of stator II controls vertical deflection, a circular motion of the spot on the screen of the cathode-ray tube is produced in a way very similar to that explained in section IX, TM 11–466, and Navships 900,016.

(2) The radial position of the spot at any instant is controlled by the waveform of the signal applied to the rotor of the transformer.

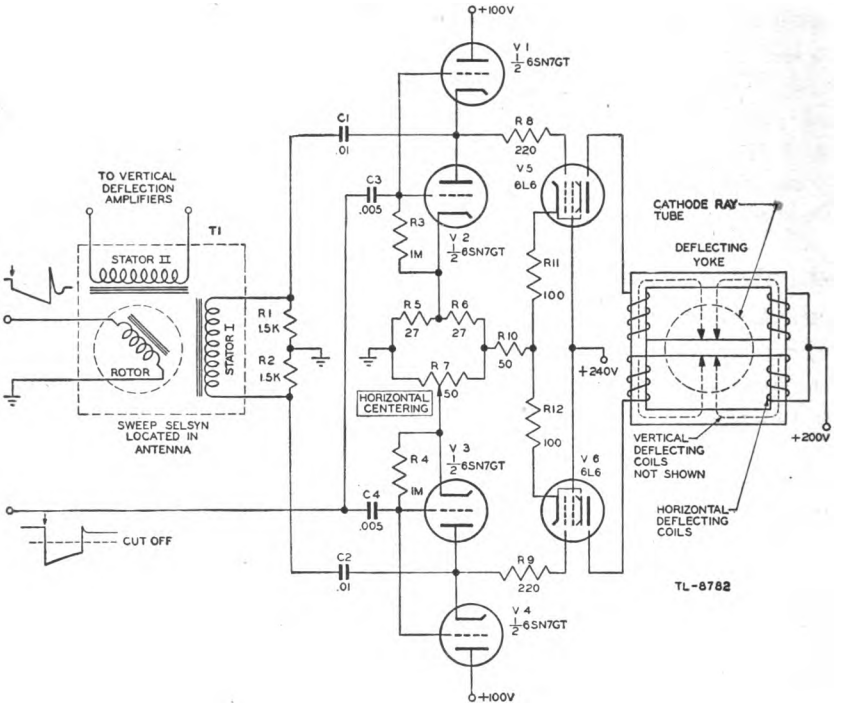

Figure 231. Selsyn transformer circuit for producing rotating sweep.

Because the deflecting coil has resistance associated with its inductance, it is necessary to apply a trapezoidal voltage to the rotor of the selsyn transformer. To produce a linear sawtooth current in the deflecting coil for a short range sweep, the trapezoid is distorted by the addition of an extra peak at its leading edge to permit fast charging of the distributed capacitance in the deflecting coil so that the sweep may start at the proper velocity at the time of the transmitted pulse. A sawtooth voltage can be used for long range sweeps because nonlinearity of the sweep near zero range is of no consequence. The sweep must be gated to provide a time interval in which the current in the deflecting coil can return to its starting value.

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(3) Since the sweep is generated 800 times per second and the antenna rotates at a maximum speed of 1 revolution per second, the output of the stator coils of the selsyn transformer is 2 trains of trapezoidal voltages of which the amplitudes are modulated by 2 sine waves 90° out of phase. The output of stator I controls the current in the horizontal deflecting coils; the other output controls the current in the vertical deflecting coils. The actual deflection is caused by the magnetic field which is the resultant of the two fields controlled by the two outputs of the selsyn transformer. Thus a change in the angular position of the antenna produces an equal change in the resultant direction of the magnetic deflecting field that causes the radial deflection of the trace.

(4) A detailed circuit for producing the horizontal component of the magnetic deflecting field is shown in figure 231. An identical circuit, fed by stator II, is used to produce the vertical component. The output of stator I is applied to the grids of V5 and V6, two type 6L6 tubes operated in push-pull. The windings on the deflecting yoke are such that when the tubes conduct equally the fields cancel. The dotted arrows on the diagram of the yoke indicate the directions of the magnetic lines. As the current in one tube is caused to rise by a signal on its grid, that in the other falls, and the result is a net magnetic field in one or the other direction.

(5) Tubes V1 and V2 are used to clamp the grid of V5 at a definite potential in the time interval between sweeps, and V3 and V4 clamp the grid of V6 (sec. VII, TM 11–466 and Navships 900,016). The grid of V2 is connected to the cathode through the grid leak so that during the time when no sweep is applied V2 has zero bias. However, V1 is biased by the drop across V2 since the grid of V1 is connected effectively to the cathode of V2. If at the end of the sweep time the grid of V5 returns to a potential higher than the normal value established of V1, the bias on V2 is increased. Tube V1 then becomes effectively a higher resistance, but the bias on V2 remains at zero so that the resistance of V2 is nearly constant, making the potential at its plate and at the grid of V5 decrease to the normal value. Conversely, a decrease in grid potential of V5 would reduce the bias on V1, causing V1 to become a lower resistance to raise the potential. Thus any change in the potential at the grid of V5 is counteracted by a change in the relative resistances of V1 and V2 which are established initially by the voltage divider R5 and R6. In a similar way V3 and V4 clamp the potential at the gride of V6 during the no-sweep time to a value which is controlled by the setting of R7. During the sweep interval the clamping tubes are held inoperative by a negative pulse on their grids in order that the sweep voltages can be applied to the grids of V5 and V6.

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(6) Selsyn transformer T1 in figure 231 can be replaced with a conventional selsyn generator by using the arrangement shown in figure 232. The primary winding is the rotor, as in T1. The three secondary windings are spaced 120° apart physically so that the three maximum

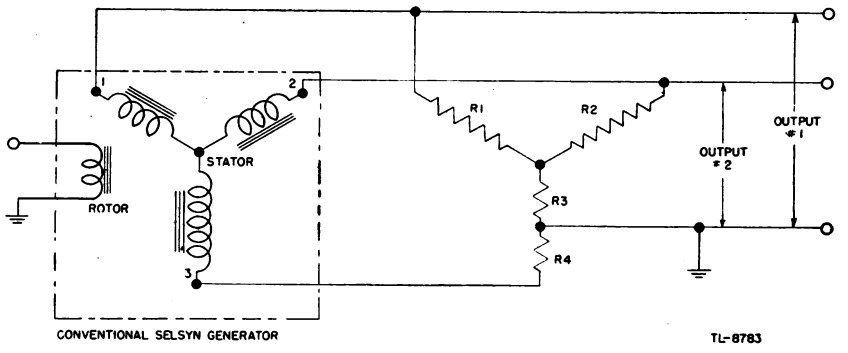

Figure 232. Conventional selsyn used to provide two output voltages.

induced voltages occur at settings of the rotor spaced at like intervals. The voltages induced in stators 1 and 2 combine in the resistance network with that induced in stator 3 in such a way that the rotor position which causes output 1 to be a maximum is always 90° away from the position that causes output 2 to be a maximum.

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Section X
Primary Power and Control Circuits

55. PRIMARY POWER SOURCES.

a. Requirements. (1) The amount of power necessary to operate radar equipment will depend upon the purpose for which the set is designed. Present large long-range installations may require up to 20 kilowatts of power, using a 60-cycle, three-phase, 208-volt source. Interception and gun-laying types may require up to 12 kilowatts of power from a 60-cycle, 120-volt source.

(2) Airborne equipment is usually operated from the plane's battery and generator and requires from 40 to 125 amperes from a 24- to 28-volt source. Since this is an excessive power drain from the battery alone the set is normally used only when the generator is charging the battery. Inverters, vibrators, and dynamotors are employed to convert the 24-volt direct current to the various a-c and d-c voltage ranges required.

b. Commercial power. The maintenance of an engine-generator set frequently requires more time and personnel than the maintenance of the radar set itself. Because of their convenience and greater dependability, commercial sources of power are used whenever available. Transformers can be used to give any desired voltage, and, where power is available at all, either single-phase or three-phase can usually be had.

c. Engine-driven generators. (1) It is standard practice to provide an engine-driven alternator of more than ample capacity to furnish power for a radar set where weight is not a prime consideration. This extra margin of capacity insures good regulation and less trouble under field conditions. In the larger sizes, 25 kilowatt and above, either Diesel or gasoline engines may be provided. In the smaller sizes gasoline engines are used exclusively. The Diesel unit has the advantage of greater fuel economy, using about half the volume of fuel as compared to a gasoline unit of similar rating. This is a great saving where transportation is a problem. However, a Diesel engine requires a more complicated or heavier starting system than a gasoline engine. The usual system in the sizes used is to provide a heavy-duty starting motor operating from a 24-volt battery,

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or an ignition system for starting on a gasoline cycle. The engine is run for about one minute on the starting motor or on the gasoline cycle to allow it to warm up, after which it is switched over to the Diesel cycle. From the maintenance standpoint the gasoline engine

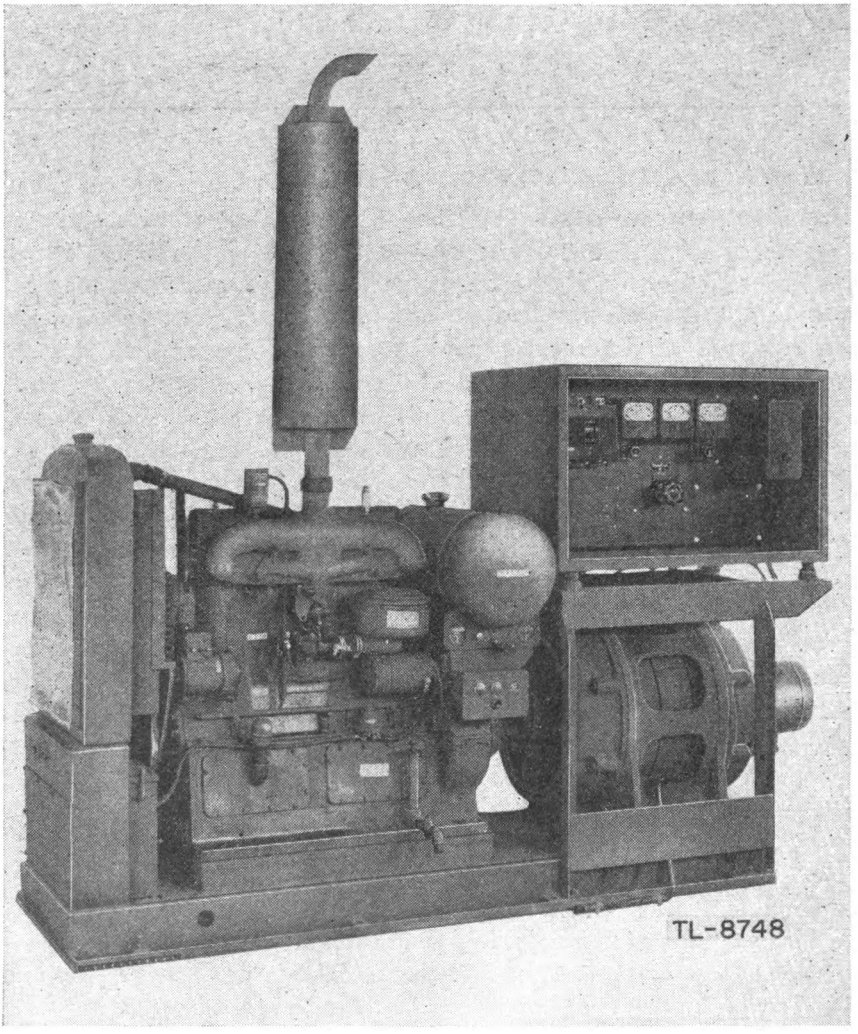

Figure 233. Gasoline engine-driven generator set, 32 kva.

is somewhat simpler and easier to handle; however, it requires attention oftener. A typical gasoline-engine generator set is shown in figure 233.

(2) An alternator consists primarily of a rotating winding, a stationary winding, slip rings, and a source of direct current for the field supply. In the most common types the rotor is the field, direct cur-

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rent being supplied to it through slip rings. This allows the small d-c field current to be handled by the slip rings and brushes, while the heavy alternating current is drawn from the stationary winding. The d-c field supply is usually a small generator mounted on the alternator shaft. A three-phase alternator has three stator windings spaced 120 electrical degrees apart. When such a system is used it is usually 208-volt, Y-connected. The three windings are connected as shown in figure 234, giving 208 volts between any two of the outside terminals, and 120 volts between any one of the outside terminals and the center or neutral connection. This gives both a three-phase and a single-phase source of power, the three-phase system being more desirable for some motor and rectifier applications.

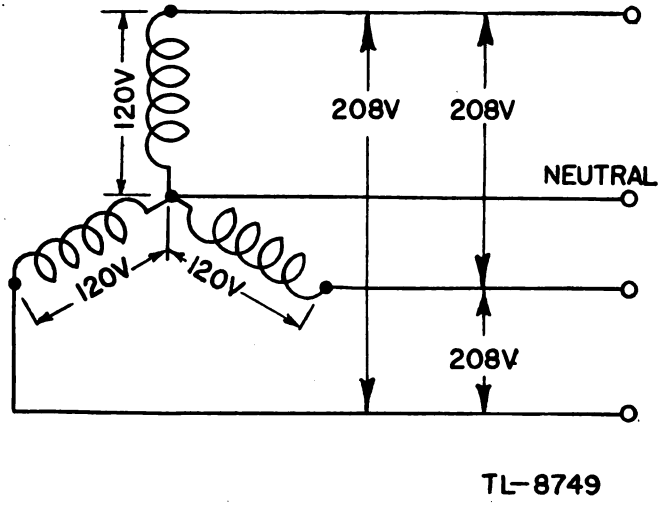

Figure 234. Y-connected three-phase system.

(3) A control panel is mounted on the engine generator set or located at some spot convenient for operation. On this panel are located the voltmeters, ammeters, frequency meters, the voltage regulator, and the switches necessary for operation of the generator. Where weight and space are of prime importance small high-speed machines are used. Such generators may be operated at a high frequency, often over 1,000 cycles per second. The use of a high frequency allows transformers as well as the generator to be constructed with much less iron than would be necessary for 60 cycles, resulting in a much lighter unit. Such a generator is shown in figure 235.

d. Rotary conversion equipment. (1) To change one d-c voltage to another, direct current to alternating current, or one frequency of alternating current to another, rotary conversion equipment may be used. Alternating current is converted to direct current

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through the use of rectifiers, unless high current is needed, when rotary conversion may be used.

(2) A *dynamotor* is a rotating d-c machine used to obtain a higher or lower voltage than is obtainable from the source. It is essentially

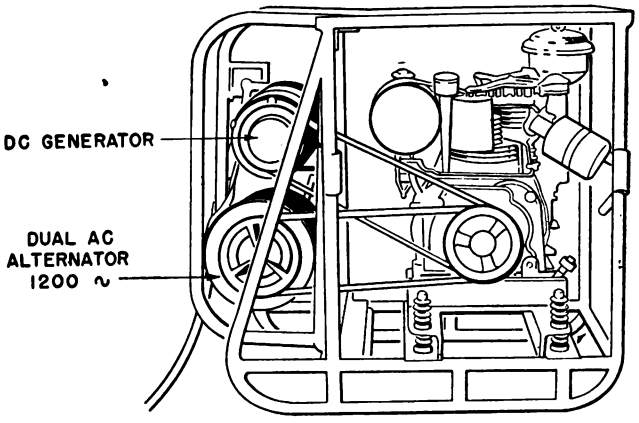

Figure 235. Light-weight engine-driven generator rated at 1,200 watts, 1,200 cycles per second, and 490 watts direct current.

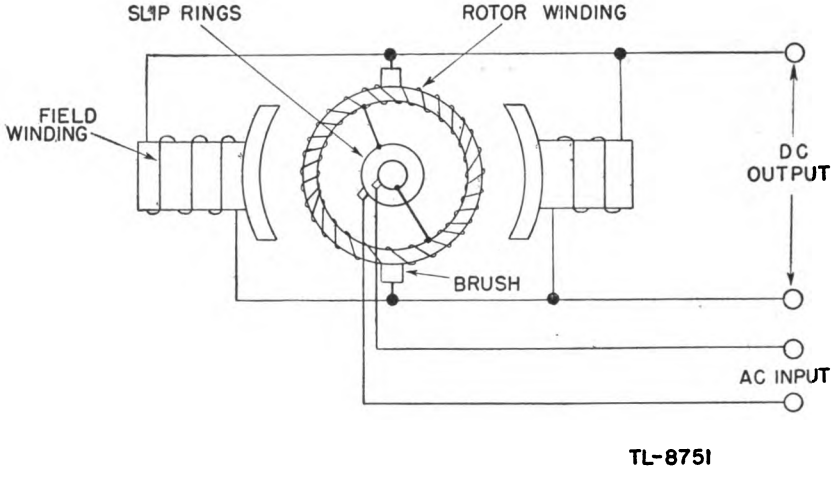

Figure 236. Simplified schematic diagram of rotary converter.

a motor and generator built into one unit having two or more windings on one armature and two or more commutators. The commutators are usually located at opposite ends of the shaft and the windings may occupy the same armature slots. Since both input and output windings are on the same armature, the field is common to both generator

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and motor winding. In some cases two separate armatures may be used, rotating in a field whose windings and poles are extended over both armatures.

(3) A *rotary converter* is a machine used to change alternating current to direct current. It is very much like a d-c generator except that two slip rings are connected to commutator segments spaced 180 electrical degrees apart (fig. 236).

The steady d-c voltage is equal to the peak a-c voltage if there is only one winding. If any other voltage ratio is required, separate input

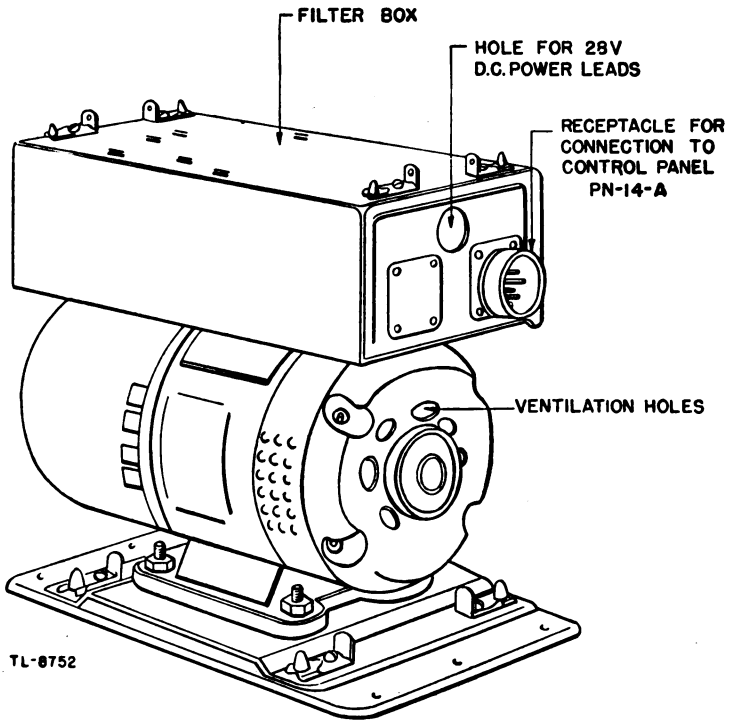

Figure 237. Inverter unit for airborne equipment.

and output windings must be used. If the d-c output is an extremely high voltage some provision must be made to excite the d-c field from a separate winding supplied by another source. The motor action is that of a synchronous motor.

(4) The function of a rotary converter may be reversed, operating with direct-current input and alternating current collected from the slip rings. It is called an *inverter* when operating in this manner. When the same armature and field are used for both a-c and d-c sections the machine is very unstable. For this reason the inverters found in radar equipment usually have two armatures and two fields, functioning as a motor and generator built into a single unit. Figure 237

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shows a typical inverter used in aircraft equipment. A unit of this type requires a number of filter and control circuits. Figure 238 is a circuit diagram of an inverter unit. The field of the motor section is compounded to give better speed regulation under a varying load in order to provide reasonably constant frequency.

e. Vibrators. (1) Another method of obtaining alternating current from a d-c source is to use a vibrator. In general practice, however, a vibrator is used in a power supply to change direct current

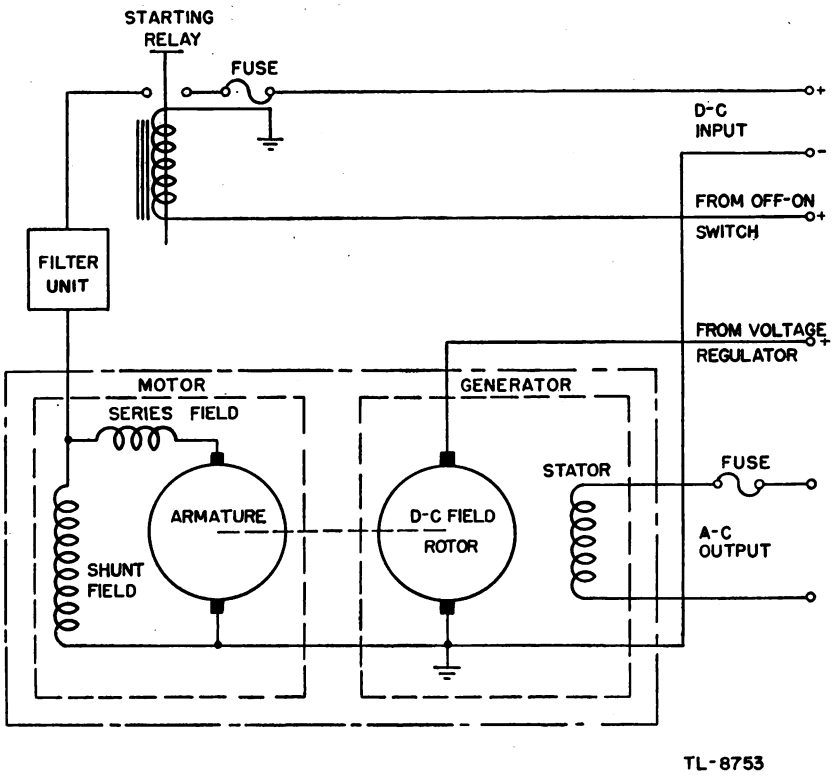

Figure 238. Schematic circuit diagram of inverter.

from a low-voltage source, such as a battery, to a higher d-c voltage. This type of power supply when used within its rated limits is very dependable. The life of the vibrator unit itself approaches about half that of an ordinary receiving tube. One of the chief advantages of the vibrator power supply is that the only item which has to be replaced often is the vibrator itself, which is inexpensive and easily installed. A full-wave vibrator is shown in figure 239. Vibrators are available in sizes capable of handling up to 100 watts of power. This maximum rating limits their use to applications requiring very little power, such as small receivers.

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(2) A vibrator-circuit diagram is shown in figure 240. When power is applied to the unit, current flows through one half of the transformer primary, and through the magnet coil of the vibrator. The field set up by the coil attracts the vibrator reed, closing contact No. 1. The closing of the contacts shorts out the coil and causes a

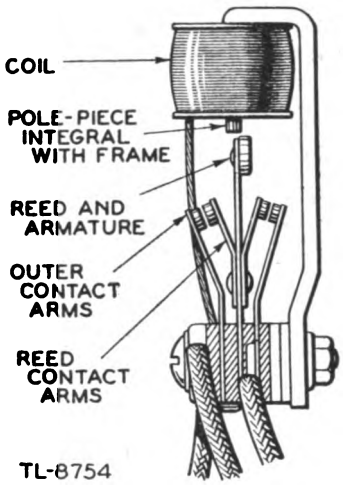

Figure 239. Full-wave vibrator.

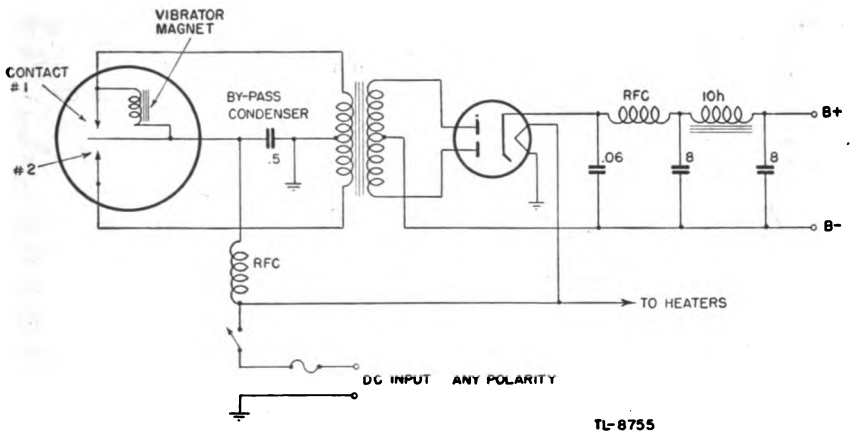

Figure 240. Schematic diagram of vibrator power supply.

large current to flow through the transformer primary. The field of the coil collapses because of the short across the coil, and releases the vibrator reed. The reed is bent by the attraction of the coil, so that when it is released it springs back to close contact No. 2. These contacts connect for a short time the other half of the transformer winding to the d-c power. It will be noted that the instant contact No. 1 opens,

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the field of the magnet begins to attract the reed. The field builds up slowly so that the full attraction is not felt immediately. In addition the reed is positioned nearer to contact No. 2 than to No. 1 and the reed need travel only a short distance beyond its normal position to close contact No. 2. The switching action of the vibrator reed causes current to flow first in one half of the transformer in one direction and then to flow in the other half in the opposite direction. This produces an alternating flux which induces an alternating voltage in

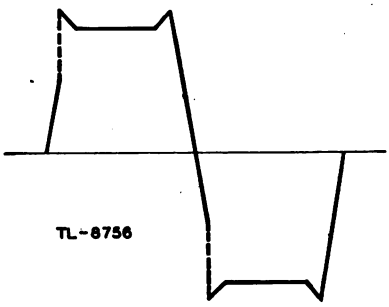

Figure 241. Waveform produced by vibrator.

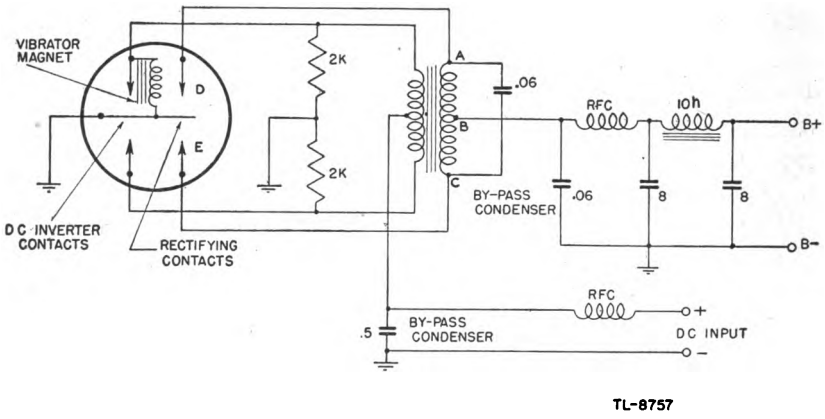

Figure 242. Synchronous or self-rectifying vibrator power supply.

the secondary. By proper design of contact springs and the vibrating reed a reasonable waveshape, similar to that shown in figure 241, may be produced.

(3) A synchronous or self-rectifying vibrator supply is shown in figure 242. In this type an additional set of contacts is provided for rectifying. The rectifying contacts are connected to the secondary of the transformer. When the vibrating reed is drawn to one side and contact *D* is closed, terminal *A* of the secondary of the transformer is connected to ground. The polarity of the transformer during this first half cycle is such that terminal *A* is negative. Dur-

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ing the next half cycle the vibrator reverses, changing the direction of the current through the primary, and reversing the polarity of the secondary, terminal *C* now being negative. Contact *E* is closed, which connects the negative terminal *C* of the secondary to ground. The center tap of the secondary, terminal *B* is always positive with respect to the particular secondary terminal that is grounded by the vibrator contacts so that terminal *B* is the positive side of the d-c output and ground is the negative side.

(4) All vibrator units require some filtering to prevent feeding disturbances, caused by the sparking contacts, into the radar set through the power leads. This is done by the air-core choke coils and bypass condensers shown in figures 240 and 242.

f. Rectifiers. (1) Rectifier power supplies are used for relays and other control-circuit applications, in field supplies for rotating machinery, and in supplying all the various vacuum tubes in the radar set. Their efficiency will vary from 50 percent for a small unit to approximately 75 percent for the very large ones. From the maintenance point of view a rectifier is more nearly trouble-free than rotating machinery. High-vacuum rectifier tubes have a life of from 1,000 to 4,000 hours depending on type and application, while the life of a mercury-vapor tube may be up to 15,000 hours. Various types of rectifiers and rectifier circuits are discussed in section VI, TM 11-466 and NavShips 900,016. A typical rectifier for a high-power radar set is shown in figure 243.

(2) The power requirements for rectifier supplies vary from a few watts to about 3,000 watts for some large transmitters. Copper oxide and selenium rectifiers are commonly found where low voltage and low powers are required, as in control-circuit and relay applications, and in field supplies for some small rotating machines. High-vacuum rectifier tubes are used where high voltages are required. These vary from the small receiver power supply which produces 250 volts, to a large transmitter power supply which provides 15,000 volts. A tube capable of supplying high voltage at high power is shown in figure 244. Mercury vapor tubes are used where a heavy current is needed at from 700 to 5,000 volts but not for extremely high voltages, because the inverse voltage may cause arc-back if the peak inverse voltage exceeds about 10,000 volts.

g. Regulators. (1) Many types of regulators are used in radar sets. Manual regulators are usually either potentiometers, variable resistors, or variable auto transformers such as variacs and transtats. Automatic regulators for holding the output voltage of a generator or other source of primary power at a desired value are usually mechanical in nature instead of electronic. Regulators are needed because all power sources have some internal resistance or

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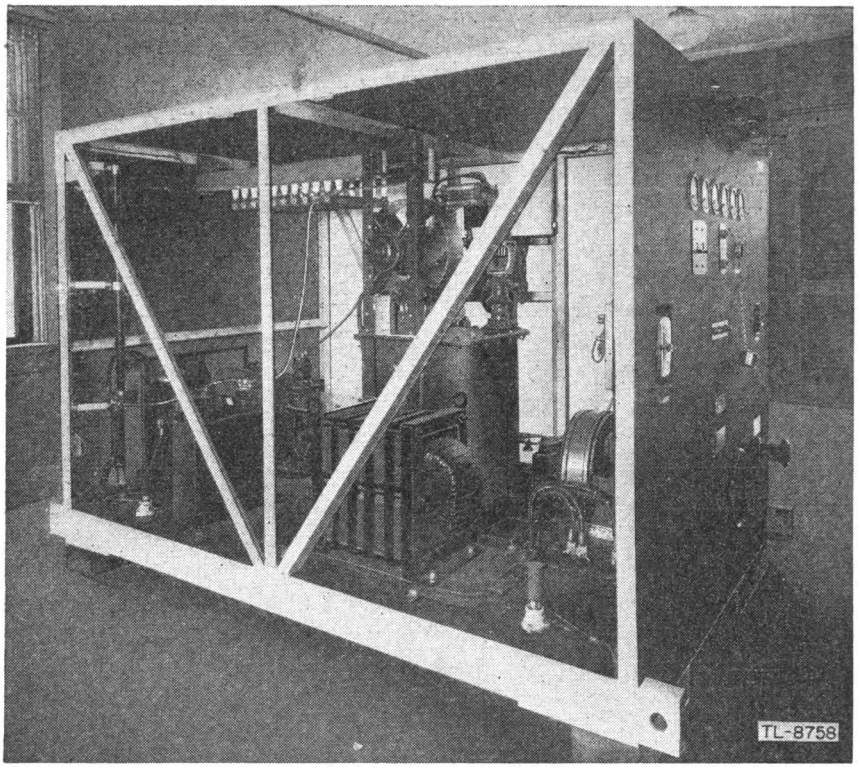

Figure 243. Rectifier for early-warning radar set.

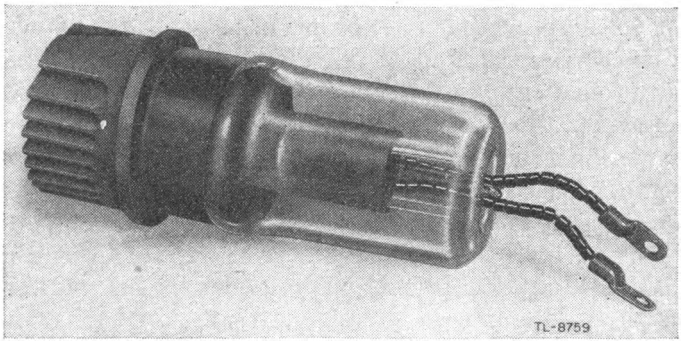

Figure 244. Heavy-duty high-vaccum rectifier tube.

reactance so that, as the load is varied, the output voltage changes. The output voltage of an a-c generator is controlled by adjusting the field rheostat of the exciter, which in turn varies the field current of the generator. Automatic voltage regulators control the generator by controlling the field of the exciter. There are three types in general use: the vibrator, the carbon pile, and the silverstat.

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(2) When a vibrator type of regulator is used, the exciter field rheostat is set so that the a-c voltage of the generator is low. If the field rheostat of the exciter is shorted out the a-c output voltage increases to a point above the normal voltage. By alternately opening and closing the short-circuit around the exciter field resistance, and by varying the time open with respect to the time closed, the average voltage can be held to the proper value. A vibrator-type regulator circuit is shown in figure 245. The regulator magnet coil is excited by the a-c output voltage of the generator, producing a 120-cycle-per-second flux variation. The floating armature tends to vibrate

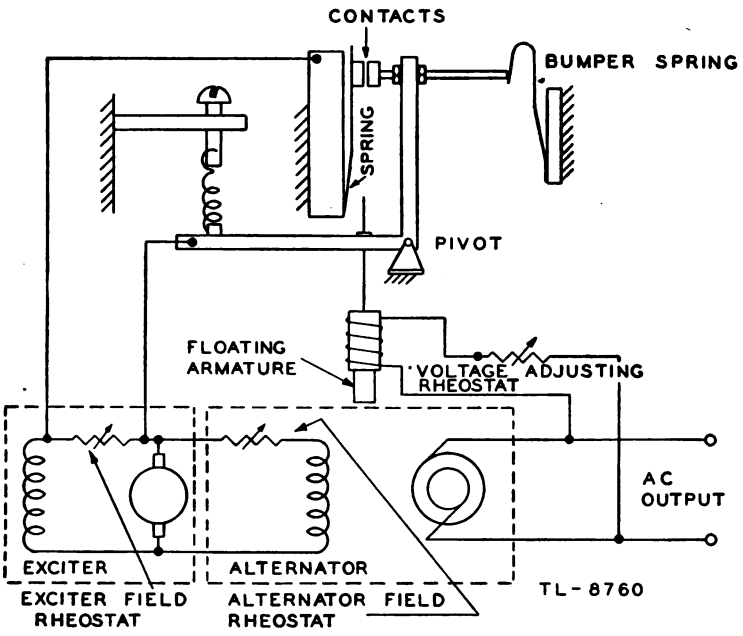

Figure 245. Vibrator type voltage regulator.

at 120 cycles per second because of the flux variations. The vibration of the armature is transmitted to the contact arm opening and closing the contacts. When the a-c output voltage is caused to drop by an increased load, the magnetic attraction is decreased and the weight of the armature has more effect on the vibrator linkage, causing the contacts to stay closed for a longer period of time during each vibration. Closing the contacts for a longer period of time causes the exciter field resistance to be shorted for a longer time during each cycle and the a-c output voltage rises above its previous value. The process is reversed when the voltage is too high. The magnetic attraction on the armature is greater, causing the effective weight of the armature to decrease, so that the contacts stay open longer

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on each vibration and the voltage drops. In actual operation there is a slight oscillation of voltage about the proper value, giving the correct average voltage output. Adjustment to the desired regulated a-c voltage can be obtained by varying the voltage control which is in series with the coil of the electromagnet.

(3) The carbon-pile type regulator operates by placing in the exciter field circuit a resistor that can be varied automatically. This resistor consists of a stack of carbon disks and the resistance across

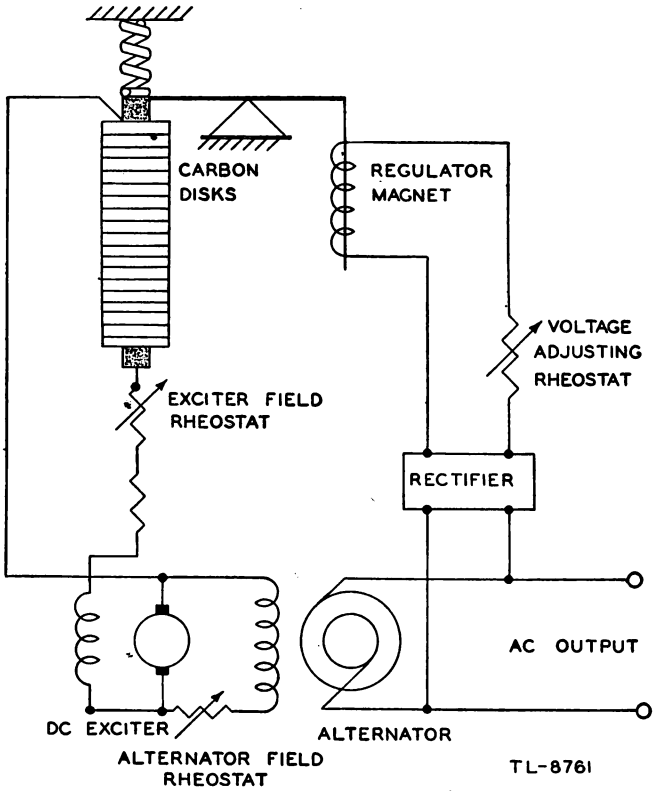

Figure 246. Carbon-pile voltage regulator.

the stack depends on the pressure on the stack. The pressure change is accomplished by an electromagnet controlled by the a-c output voltage. A schematic diagram of such a regulator is shown in figure 246. If the load is increased and the a-c voltage drops, the current in the electromagnet is reduced and the pressure on the disks is increased. This reduces the resistance and the exciter field current increases. An increase in exciter-field current increases the exciter output and consequently increases a-c output voltage to the correct value. The linkage between the electromagnet and the carbon pile must be properly

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adjusted to prevent overcorrecting or hunting. This would cause the voltage to oscillate about the correct value before coming to rest. A filter usually is provided to prevent disturbances from leaking back through the power system. To set the output voltage to a desired value the voltage-adjusting rheostat must be varied. Changing the exciter field resistance or the alternator field resistance would merely cause a voltage variation that the regulator would try to overcome.

(4) The silverstat regulator is similar in operation to the carbon-pile regulator. A multi-tapped resistor is used in place of the stack of carbon disks. The taps on the resistor are connected to silver contacts by means of flat single-leaf spring conductors which are insulated

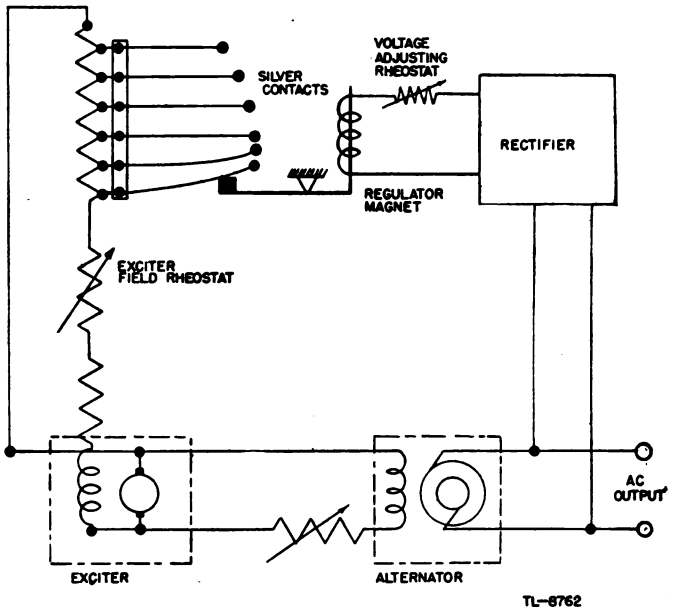

Figure 247. Silverstat voltage regulator.

from each other. These contacts are arranged in a row so that as the pressure is increased on one end of the row the number of contacts closed is increased, shorting out more of the resistance. Figure 247 is a schematic diagram of a silverstat type voltage regulator. If the output load increases or decreases the output voltage changes. The electromagnet then varies the pressure on the row of contacts, increasing or decreasing the amount of resistance in the exciter field that is shorted out. This change in exciter-field resistance varies the exciter-field current, bringing the a-c output voltage to the proper value. A rectifier is normally included in the electromagnet circuit to eliminate chatter of the regulator. In order to eliminate vibration caused by the a-c variations, a copper oxide or selenium rectifier changes the a-c

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output of the generator to pulsating direct current. The current for the electromagnet is supplied by the rectifier through a rheostat. The pull of the electromagnet is constant and proportional to the output voltage.

56. CONTROL DEVICES.

a. Relay Principles. (1) A relay is a switch which is operated electromagnetically. It is designed to open or close a circuit when the current through its exciting coil is started, stopped, or varied in magnitude. The component parts of a relay are a coil wound on an iron core and an armature that operates a set of contacts. A simple relay and circuit are shown in figure 248. Closing the operating switch S_1 allows current to flow through the coil, energizing the electromagnet and drawing the armature upward. The action of the armature closes the contacts, thereby applying power to the load.

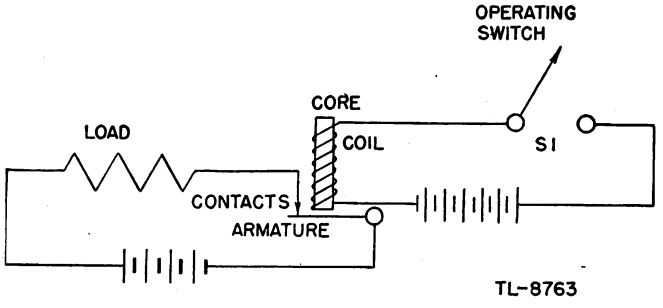

Figure 248. Simple relay circuit.

More contacts can be added to the armature so that other functions may be accomplished.

(2) The operating speed of a relay is determined by the time between the closing of the coil circuit and the closing of the relay contacts. In small, specially designed relays, the operating speed may be as low as 1 millesecond. The operating speed of a relay may be increased by any system that reduces eddy currents in the core. Another method is to place a resistor in series with the relay coil and increase the operating voltage. This will increase the speed of closing because at the instant power is applied to the relay all the voltage will appear across the relay coil, causing the magnetic field to build up faster. Slow action can be obtained by placing a heavy copper sleeve over the core which is in effect a shorted turn. The action of the current in this shorted turn is to oppose the field as it builds up or collapses, thus delaying the operation of the relay.

(3) A-c relays are slow in operation primarily because they must be made rather heavy to prevent chatter and vibration caused by the

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alternations of the field. Vibration can be eliminated to a certain extent by placing a slot in the core and putting a heavy copper washer around one half of it. This divides the flux passing through the armature into two portions about 90° out of phase. The zero values of the magnetic attraction do not come at the same time and a more uniform force is applied to the armature.

(4) Various materials are used for contacts, depending on the amount of current to be handled. Large power relays usually have copper contacts and utilize a wiping action to insure a good connection. Small relays may use silver or some silver alloy, while in some applications tungsten or some very hard material may be used which will prevent contact burning or oxidation. In general, relays that open

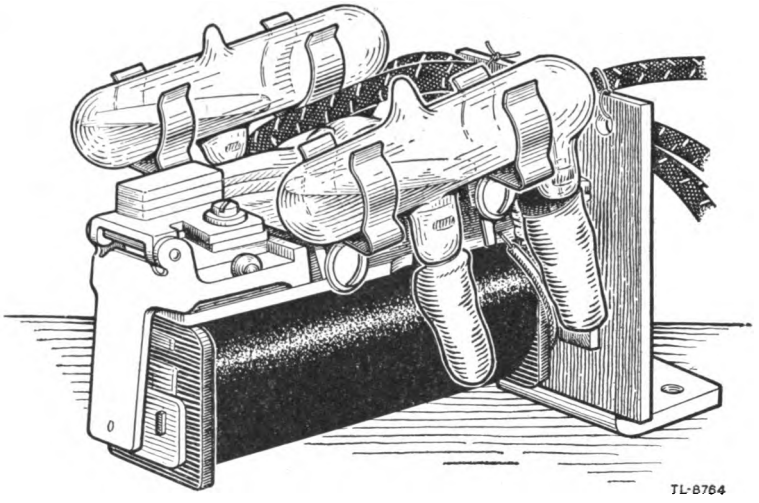

Figure 249. Mercury contact power relay.

and close with a fast positive action cause much less trouble than those that operate slowly.

b. Power relays or contactors. (1) Heavy-duty relays called contactors are used extensively for remote-control electromagnetic switching. For these applications a relatively small amount of control power may be used to energize the holding coil of a contactor whose contacts are made heavy enough to handle any required amount of power. Such contactors are used in radar for applying power to electrical devices such as motors, and filament and plate circuits of vacuum tubes. For the last mentioned use the contactor is normally connected in the primary of the filament or plate-circuit transformers.

(2) Figure 249 shows a mercury contact relay. This type relay is used for currents between 1 and 15 amperes. The mercury and contacts are sealed in a glass tube that is filled with some inert gas to prevent

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the contacts from oxidizing. The mercury normally rests in one end of the tube. When the armature is actuated, the tube is tilted and the mercury flows to the other end of the tube, either opening or closing the contacts according to the design.

(3) Figure 250 shows a typical contactor of the clapper type. This contactor has a swinging armature pivoted at one end, with the contacts at the other. The clapper action causes the contacts to come together with a sliding motion which tends to make them self-cleaning. Other auxiliary contacts for various control functions may be mounted on contactors of this type.

(4) Figure 251 shows another type of contactor known as the solenoid relay, which operates with an up motion in the vertical plane. When the coil is energized the plunger or armature snaps upward, closing the contacts, which are mounted on springs to insure

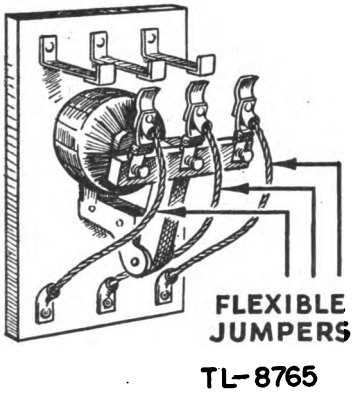

Figure 250. Clapper type contactor.

an even pressure where more than one set of contacts are used. Contactors of this type usually have silver-alloy contacts which do not oxidize easily and consequently require little attention.

c. Circuit control relays. (1) A circuit-control relay is used where the circuit functions become so numerous that operating switches for each would be complicated and time-consuming. Performing these operations with relays eliminates operational errors by causing the various functions to take place automatically in the proper sequence.

(2) Circuit-control relays may be constructed in a wide variety of shapes and sizes. The switchboard type is shown in figure 252. While this is a simple example of this kind of relay, several groups of contact springs may be used and a number of different circuits may be opened or closed. A copper sleeve giving the relay a delayed action is also shown in this figure.

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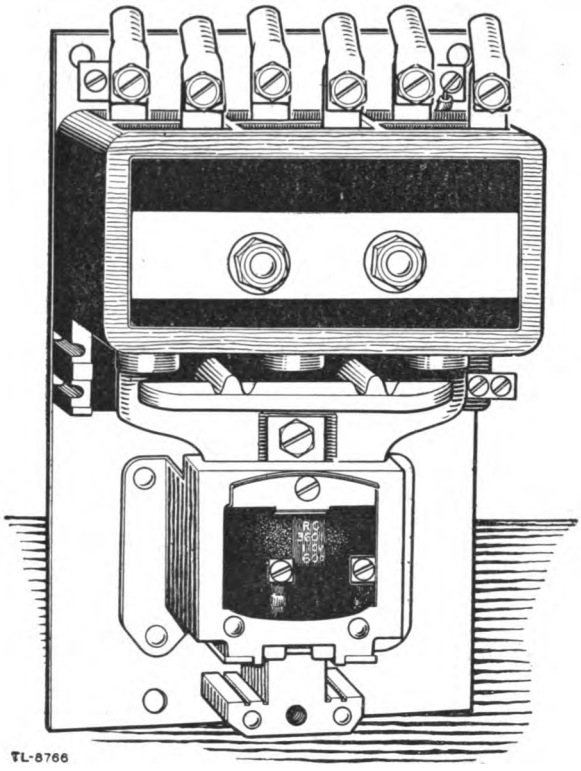

Figure 251. Power contactor.

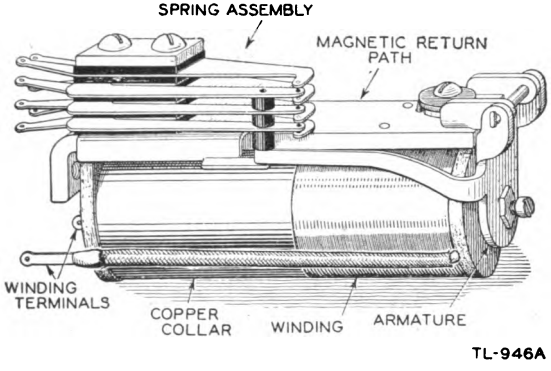

Figure 252. Switchboard type relay.

(3) An overload relay is designed so that it will break a circuit when the current through it reaches a predetermined value. A latch is frequently provided to keep the circuit open following the overload, in order to prevent the circuit from being opened and closed repeatedly while the overload exists. An overload relay may have

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a push button attached for mechanical release or it may have an additional electromagnet for remote push-button release of the latch. The latter type of relay is shown in figure 253. Coil L_1 is connected in the plate circuit of the tube to be protected. Coil L_2 is energized momentarily to reset the mechanical latch after the overload relay has operated.

d. Time-delay relays. (1) The time delay relay is used to provide a time interval between separate operations. One common form of time-delay relay uses a bimetallic element which bends as it is heated. The element is made by welding together two strips of

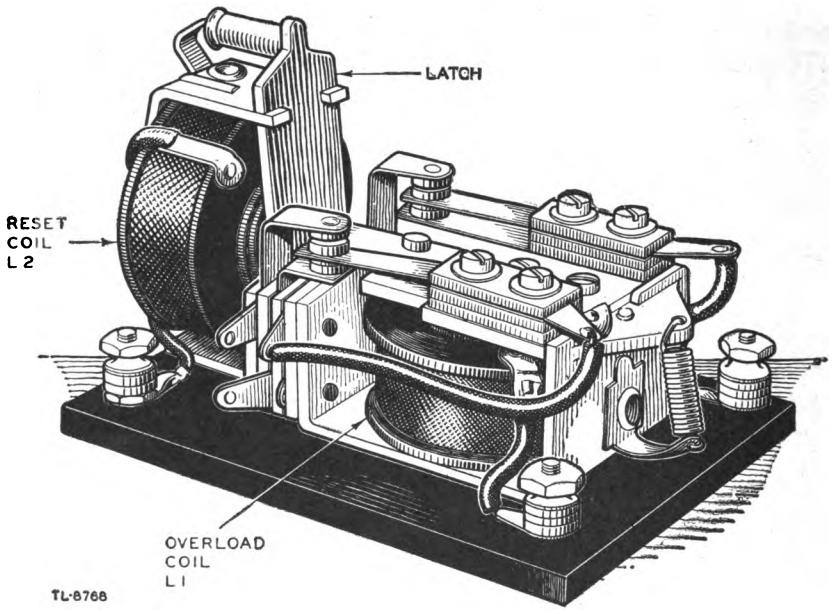

Figure 253. Overload relay with magnetic release.

different metals having different expansion rates. A heater is mounted around or close to the element. Contacts are mounted on the element itself and, as the element is caused to bend by the different expansion rates, these contacts close to operate a relay (fig. 254). The delay time for bimetallic strips is usually from ½ to 1½ minutes and is varied by using metals with different expansion rates or by increasing or decreasing the distance between the fixed and moving contacts.

(2) Motor-driven time-delay relays are frequently used. This type of relay employs a small synchronous motor and a gear train to obtain the desired delay time. A set of movable contacts is mounted on the last gear of the train and the circuit is closed when this set of contacts is turned enough to touch the stationary contacts (fig. 255). Other motor-driven time-delay relays utilize a spring action to close the relay

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contacts. The spring is released by the gear train after a given time interval.

(3) The oil dash-pot type relay is used in many time-delay applications. A magnetic coil pulls a plunger through a dash pot filled with

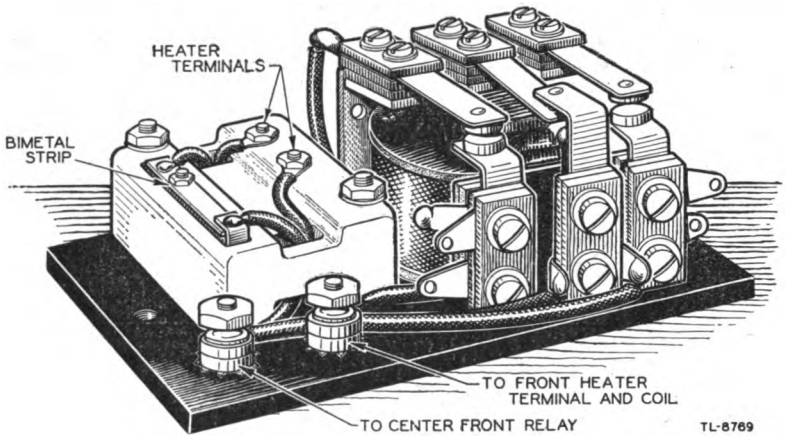

Figure 254. Bimetal time-delay relay.

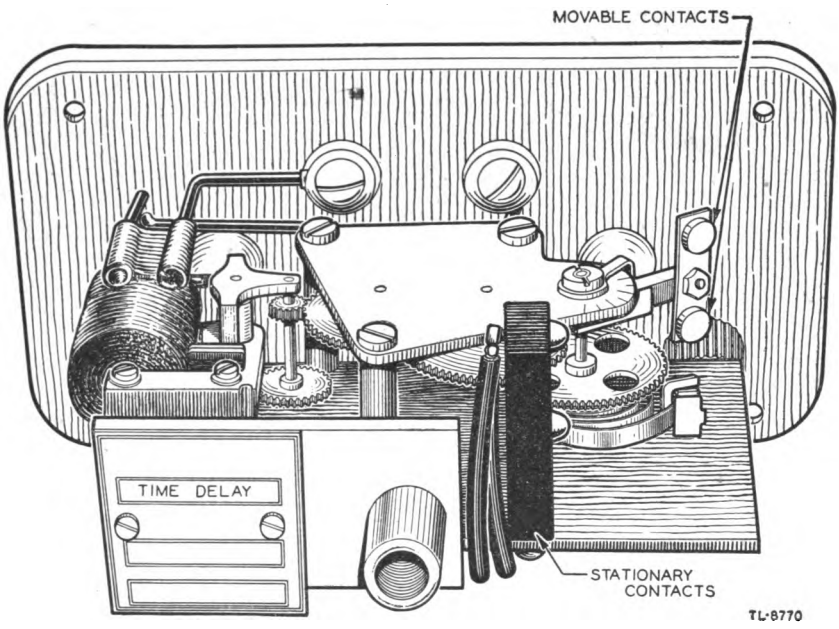

Figure 255. Motor-driven time-delay relay.

oil, the oil passing through a small hole in the plunger. The time delay can be varied by changing the size of the hole in the plunger. To make a relay of this type trouble-free, a snap action of some kind must be provided for positive closing of the contacts.

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e. Circuit breakers and fuses. (1) Some form of protective device is needed in nearly all circuits. In primary circuits where the voltage is fairly low and the current rather high a circuit breaker or fuse is generally used, and in some cases both are used. This protects the source of power from overloads and short circuits, and also prevents the equipment from being burned out.

(2) A circuit breaker is a switch that opens a circuit when a current of a certain limiting value flows through it for a given length of time. In the usual form for radar primary circuits the circuit breaker is operated by a heater element and bimetallic strip or by passing current

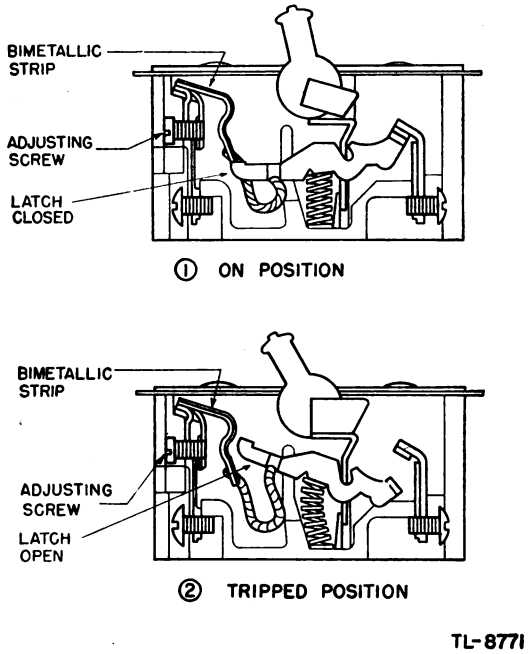

Figure 256. Low-power circuit breaker.

through the bimetallic strip itself to generate the heat. A typical circuit breaker is shown in figure 256. It consists essentially of a carefully calibrated bimetallic strip, contacts, and a means of resetting. As current flows through this strip, heat is generated and the bimetallic strip bends. Under sufficient heat it bends enough to interrupt the circuit by releasing a trip which opens the contacts. A circuit breaker of this type will carry its rated load indefinitely, it will carry a 50-percent overload for about a minute, a 100-percent overload for about 20 seconds, and a 200-percent overload for about 5 seconds. The latter time usually is long enough to allow a motor to start without tripping the circuit breaker because of the high starting current. Mag-

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netic breakers can be obtained which open almost instantly when more than rated current flows through them.

(3) The most common over-current device is a fuse. A fuse is merely a short length of wire or ribbon made of an alloy that has a low melting point and of a size which will carry a given amperage indefinitely. A larger current causes the metal to heat and melt, opening the circuit to be protected. Most fuses designed for other than home use have a delay time on overloads similar to that of circuit

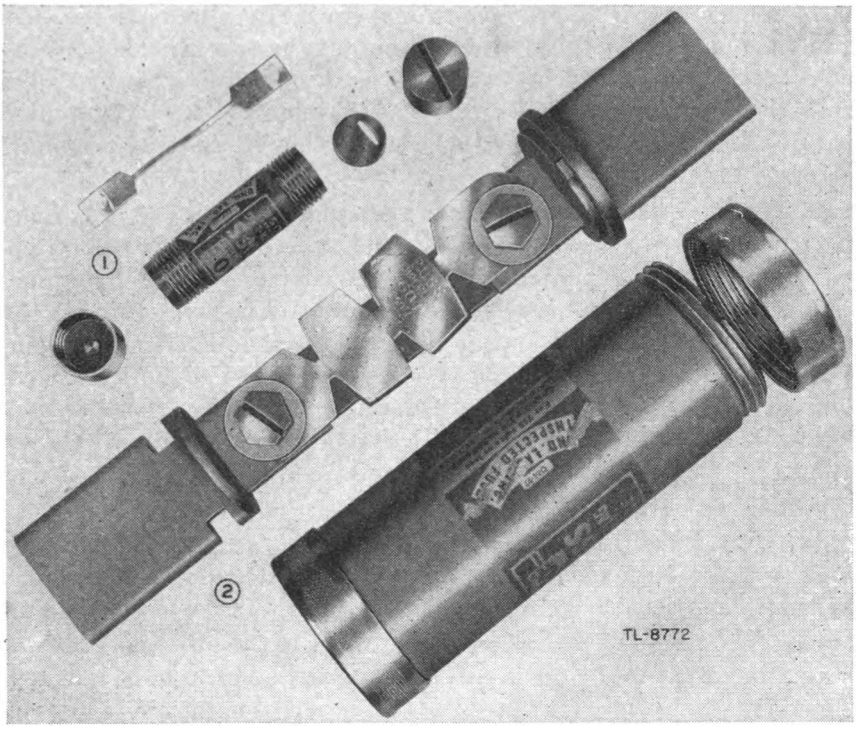

Figure 257. Removable-link cartridge fuses.

breakers. This delay can be accomplished by making the fuse link of heavy construction except in one or two short portions of its length. This allows heat to be drawn away from the small high-resistance portions, delaying the melting time, and giving the desired delay action. A fuse of this type is shown in figure 257②. Fuses are made in two types: the plug type which can be obtained in values up to 30 amperes, and the cartridge fuse which is made in sizes from a fraction of an ampere to 600 amperes or more. Sizes above 60 amperes are furnished only in the knife-blade cartridge type which provides a better contact surface.

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57. CONTROL CIRCUITS.

a. General. The primary functions of control circuits are to provide convenient operation and to protect both personnel and equipment. Relays are used where it is impractical to close switches by hand because of location, voltage, size, or number of switching operations to be accomplished. It is much more feasible to set up a control circuit, using relays to perform switching close to the components, than to bring leads carrying high voltage or heavy current to a more convenient operating position. A very important use of relays is to render high-voltage circuits inoperative to eliminate the possibility of personal injury when the circuits are not shielded or covered properly. Time-delay relays are used to protect expensive tubes from the injury that would occur if the high-plate voltage were applied before the filaments had heated sufficiently, thus eliminating personnel errors.

b. Push-button operated relay circuits. (1) A relay may be operated from a separate power source by closing a switch, but whenever possible a push-button type control is used in conjunction with a holding circuit which keeps the current flowing through the relay coil after the push button is released. The hold-in is accomplished by a set of contacts on the relay itself which short the push button. The "Start" button is normally in the open position. A "Stop" button is placed in series with the coil which is normally closed. Whenever this button is pressed the relay-coil circuit is opened and the relay opens.

(2) Figure 258① shows a simple push-button circuit that could be used to operate a filament transformer or other low-power apparatus. When the start button is pressed the relay is energized, closing the contacts. The action of the relay applies power to the load and provides a hold-in circuit to the relay, allowing the push button to be released. The relay can be opened by pressing the stop button, thus restoring the circuit to its original condition. This circuit has the disadvantage that the load current must pass through the push-button contacts between the time the button is pushed and the time the relay is closed. This limits the power-handling capabilities of the circuit.

(3) Figure 258② shows a circuit suitable for a high-voltage power supply. The push button cannot operate relay 1 until relay 2 is closed. Relay 2 is operated by the filament and interlock circuits. With relay 2 closed, relay 1 will close when the start button is pressed. An alternate path through the coil of relay 1 is provided by the lower set of contacts on relay 1 so that when the start button is released relay 1 holds in. In this case the load current does not flow through the start button.

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c. Overload protection. (1) Some form of protection must be provided for high-voltage equipment to prevent overloads caused by misadjustment or to prevent damage to other components in case one fails. While a great many refinements may be added to overload relays, such as delay and automatic resetting mechanisms, the simple type is usually found in radar equipment. A circuit giving overload protection for a high-voltage system is shown in figure 259.

(2) The overload relay is connected in the ground or low-potential side of the power supply to eliminate the necessity of high-voltage

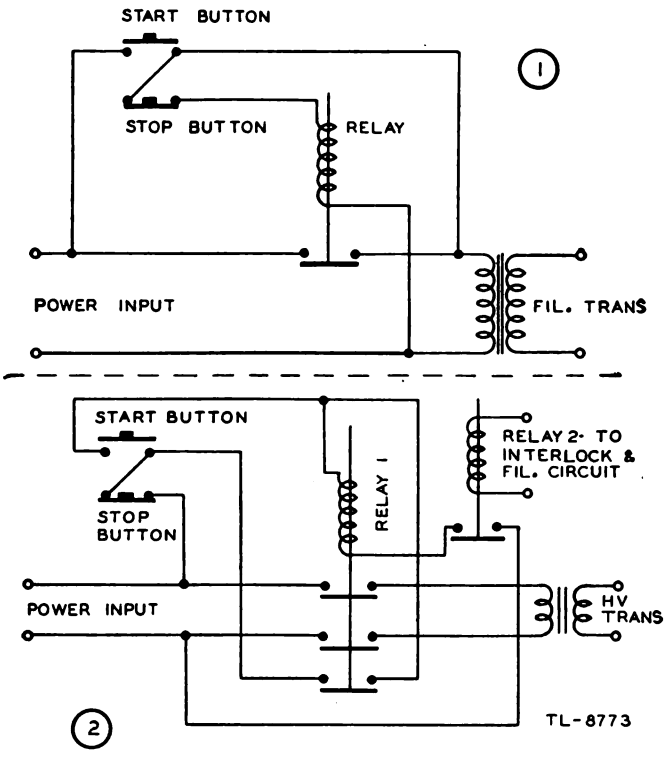

Figure 258. Push-button operated relay circuits.

insulation. It is so adjusted that when the current reaches a certain point the armature lifts, opening the contacts *A*. This opens the power-relay circuit and disconnects the primary of the high-voltage transformer. A latch is provided to prevent the armature from dropping and closing the contacts before the cause of the overload has been ascertained.

(3) Some radar units use an over-voltage relay to protect the equipment from voltage surges caused by poor regulation. The coil of this relay is mounted in series with a spark gap. The two are placed

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between the high-voltage supply and ground with the coil at the ground end. When the voltage builds up to a value that is too high, an arc is formed across the spark gap, causing current to flow through the relay. This opens the contacts and disconnects the high-voltage primary.

d. Time-delay circuits. Time-delay relays are used in circuits to provide a definite time interval between operations. The most common use of the time-delay relay in radar is to allow a definite time to elapse after filament voltage is applied before plate voltage is turned on. A circuit of this kind is shown in figure 260.

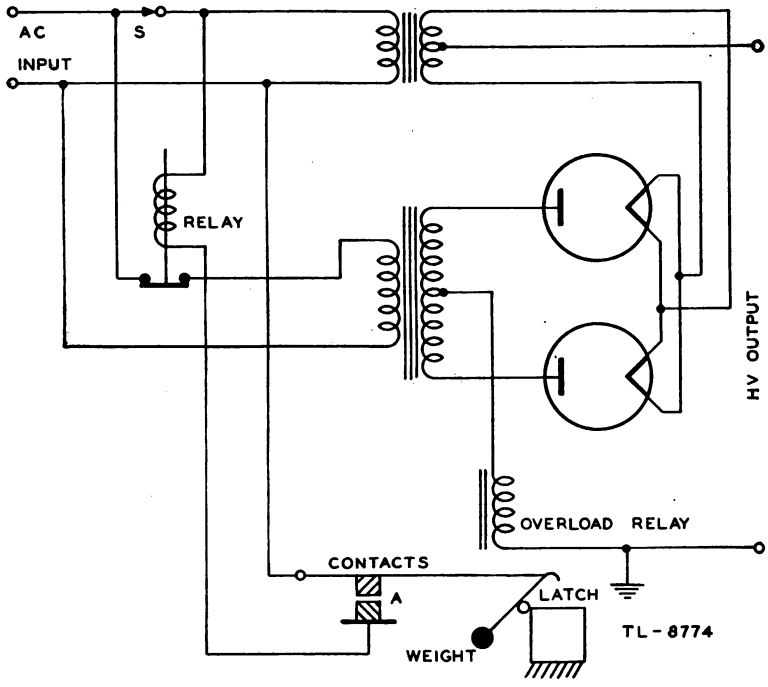

Figure 259. Overload-relay circuit.

Power is applied to the filament circuit at the same time that power is applied to the heater unit of the time-delay relay through its dropping resistor and the lower contacts of the time-delay relay. After the proper interval the bimetal strip bends sufficiently to close contacts *C*. Closing contacts *C* energizes both the holding relay and the high-voltage control relay connecting the high-voltage power transformer to the power source. Operation of the holding relay disconnects the heater unit so that the bimetal strip may cool to its normal position to prevent the high voltage from being removed and suddenly reapplied. The holding relay keeps the high voltage relay energized while the contacts *C* are open.

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e. Interlock circuits. Interlock circuits are used in a radar set to prevent one unit from being turned on before another, where damage might occur if this order were not followed. Such circuits are also used to prevent high-voltage equipment from being turned on before protective covers are placed on the equipment to prevent personal injury. In the latter case, switches are mounted behind the doors and panels in such a manner that they are closed when the covers are in place. The switches are placed in series with the holding coil of the high-voltage control relay. An interlock circuit is shown in figure 261. Power is applied directly to the filament supply and to the time-delay relay. After the time-delay relay has closed, power

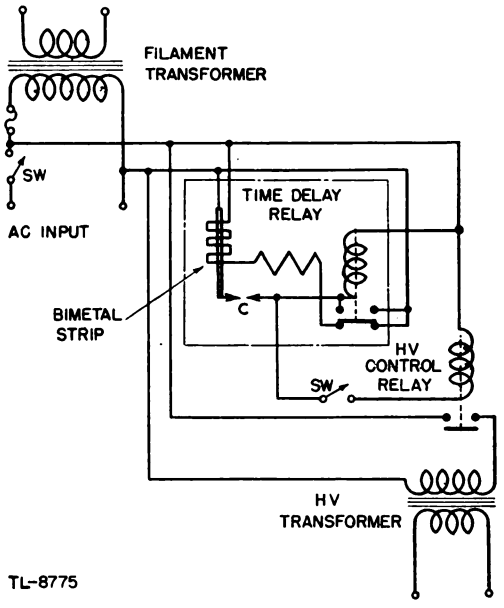

Figure 260. Time-delay relay circuit.

passes from point *A* through the time-delay relay contacts, and then through the door and panel interlock switches. From here the current goes to the transmitter and passes through the contacts of a relay which is closed by applying power to the transmitter filaments. The current then passes through the overload relay and the high-voltage transformer control relay coil to the other side of the line. If all switches and contacts are closed the control relay applies power to the high-voltage transformer.

f. Cooling water-pressure control. Some large tubes require water to dissipate the heat generated at the plate. A system of this type requires a pump, a fan radiator, and an automatic control that will cut off the plate and filament voltage in case the water ceases

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to flow. This is accomplished by the low-pressure control illustrated in figure 262. To start operation the power is applied and the start button is pressed to close the mercury switch. The start button is held in place until the water pressure is sufficient to cause the bellows to expand and hold the switch arm in the closed position. The start

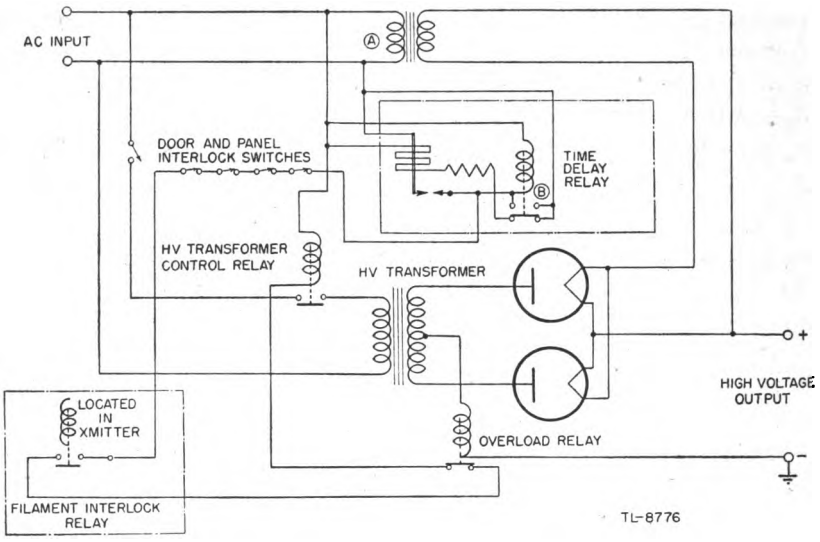

Figure 261. Interlock circuits for high-voltage rectifier.

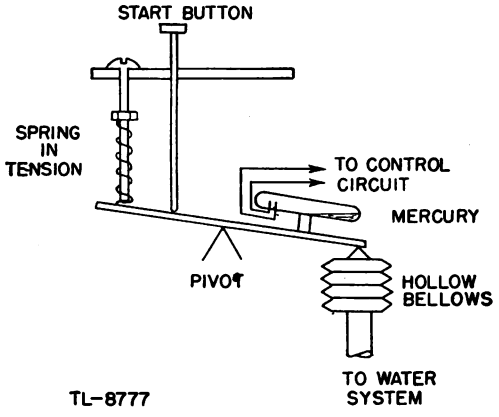

Figure 262. Low-pressure control.

button can then be released. Should the pressure drop because of pump failure or a leak, the bellows contracts, and the mercury switch opens, turning off the transmitter plates and filaments. A similar unit can be used to turn the set off in case the pressure becomes too high, as would be the case if the water lines were blocked.

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Section XI

Data Transmission and Servo Systems

58. REMOTE INDICATOR SYSTEMS AND SERVO SYSTEMS.

a. General. (1) In the operation of radar equipment it is often necessary to have the angular motion of a shaft follow accurately the motion of another shaft some distance away. If the shafts are not too far apart the motion can be transmitted by means of a mechanical linkage. However, this method is in general cumbersome and uneconomical, particularly where large amounts of torque and power are to be transferred. A method which is more flexible and more commonly used is to convert the motion of one shaft into electrical currents, transfer these currents via wires, and convert them back to mechanical motion of a second shaft.

(2) Two major applications in radar of such conversions of shaft motion to electrical currents and back to shaft motion are found in remote indicator system and in servo systems.

(3) The term "remote indicator system" refers to a device used for transmitting data or information between two points. Examples are the reading of a meter dial, the position of an antenna in azimuth or elevation, temperature readings and similar information. For such indications very little torque and energy are involved.

(4) The term "servo system" refers to a mechanism whereby a controlled shaft delivers much more power than the controlling shaft, and the action of the power-amplifying device is regulated by the *error* or discrepancy in angular position between the two shafts. An example of the servo system is the ordinary radar antenna control. Here a small handwheel is turned, and the angular error in degrees between a reference point on it and a reference point on the rotating antenna mount controls a power amplifier furnishing power to an antenna drive motor. When the two reference points are aligned, no error is present and there is no output from the power amplifier. At any other point the power amplifier produces an output which swings the antenna into alignment again. Thus the servo system has two functions: It causes one shaft to follow another in angular motion, and it amplifies the torque and power between the two.

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b. Basic antenna position indicator and servo system. (1) A basic position indicator and servo system for a radar antenna is illustrated in figure 263. In the position indicator block, G1 is a device which converts the position of a shaft attached to the antenna into electrical currents. These currents are transmitted by a cable to M1 which converts them back to shaft rotation. The shaft is attached to a pointer which indicates the antenna position on a dial.

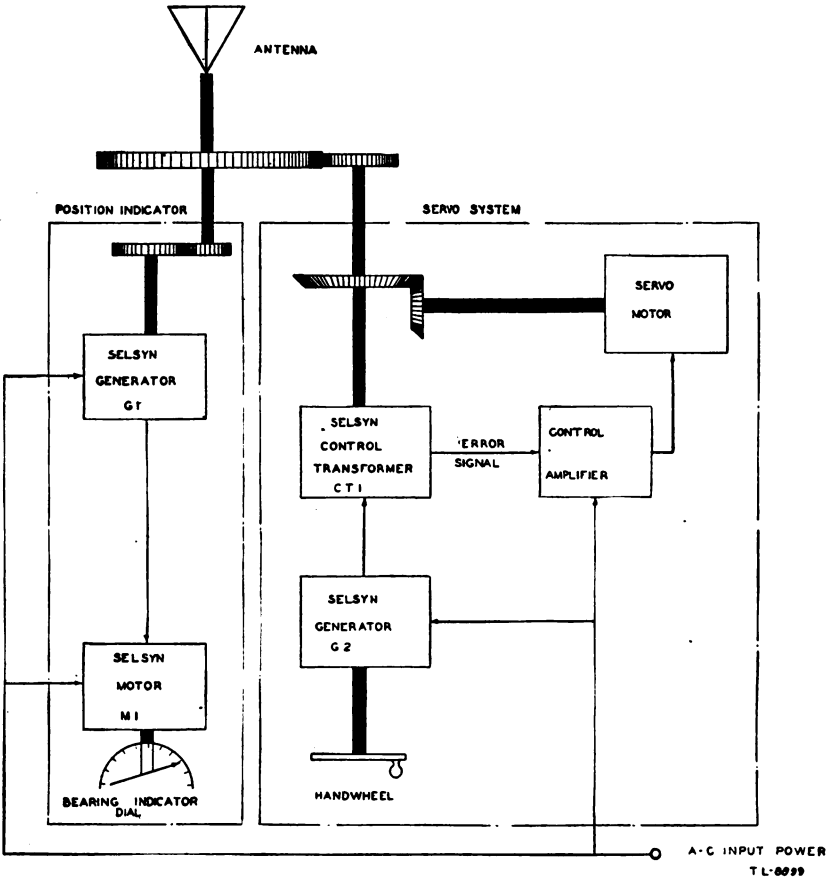

Figure 263. Basic indicator system and servo system.

For every position of the antenna the direction of the beam in azimuth thus is given by the dial reading. A similar arrangement can also be applied if desired to an elevation indication or to any other data-transmission problem.

(2) In the servo system block G2 converts the position of the handwheel into an electrical indication which is transmitted to CT1. CT1 is a device which compares the relative position of the antenna shaft with the position of the handwheel as conveyed electrically over

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the cable, and which develops an *error* voltage proportional to the difference between the positions. This error voltage is applied to the control amplifier which controls the power flow to the servo motor which rotates the antenna. Whenever the error voltage is present, the antenna is rotated in such a direction as to make the error voltage less. Thus when the antenna position corresponds to the handwheel position, there is no error voltage and the antenna comes to a stop. The control amplifier supplies the variable power to the antenna drive motor, and usually is substantially electronic in construction.

(3) The principal method of providing the electro-mechanical conversions necessary for operation of both the position indicator and the servo systems is the use of the *selsyn.* In simple indicator systems

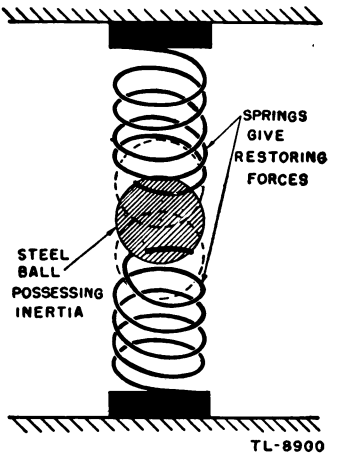

Figure 264. Mechanical demonstration of hunting.

a potentiometer also is used frequently to obtain a voltage proportional to the displacement of a shaft.

c. Antihunt considerations. (1) One problem in the application of the servo system is that of hunting. Hunting refers to the tendency of a mechanical system to oscillate about a normal position. Thus in figure 264 the steel ball, if depressed from its normal position and suddenly released, oscillates vertically because of its inertia and the forces exerted by the springs. In time the oscillation is damped out by the frictional losses of the oscillating system.

(2) A similar effect is noticed in radar equipment using a servo system to drive the antenna. Since the connection between the handwheel controlling the antenna position and the antenna itself is effectively somewhat elastic because of the action of the electrical and magnetic circuits involved, the inertia of the moving antenna

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causes it to overtravel its required position. An error voltage is developed in the servo system in the opposite direction and the antenna reverses. Successive overtravels by the antenna would be less and less, and the mechanical oscillation would die out except for one factor: there may be a time lag in the servo system which causes reinforced oscillations. In such case, the antenna would continue to oscillate or *hunt* about its normal position. This effect is equivalent to regenerative feedback in a radio circuit contributing to the setting up of an oscillatory condition.

(3) In order to eliminate hunting, which would cause harmful mechanical vibration of the entire antenna rotating system, an *anti-hunt* device or circuit is introduced. These commonly consist of arrangements to slow up the drive motor as the antenna approaches its final position. If the drive power is reduced soon enough the inertia of the moving parts causes the antenna to coast into its final position without any overtravel. In other words, the position control is made nonoscillatory, and is thus equivalent to degenerative feedback in a radio circuit.

59. BEARING-INDICATION EQUIPMENT.

a. Transmitting and receiving selsyns. (1) A *selsyn* is a device used for the electrical transmission of an angular position. Although the word selsyn (from self-synchronous) is actually a

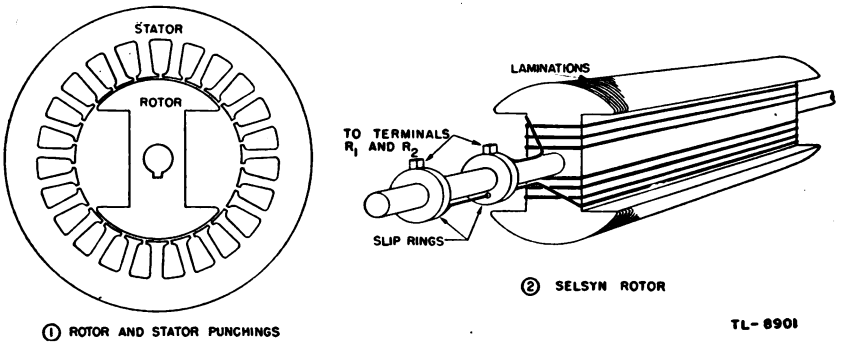

Figure 265. Mechanical details of selsyn.

trade name, it is commonly used to denote all apparatus of the same general type. Other names and trade names in current use include *syncrotie*, *autosyn*, and *synchro* (United States Navy).

(2) Essentially the selsyn has the form of a small two-pole alternator. The *rotor* (fig. 265②) is turned by a shaft mounted on ball bearings, and has a single coil of wire wound on an iron core, which is constructed of thin sheets to minimize eddy currents. The ends of the coil are connected to slip rings and thence to terminals R1 and R2

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on the frame. The *stator* is fixed in position and may act as part of the frame. It also is constructed of thin iron sheets, and has uniformly spaced slots (fig. 265①) into which are wound three separate coils. The coils are spaced 120° apart around the stator and distributed in several pairs of slots. A corresponding end of each coil is connected to a common point and the other ends are connected to terminals S1, S2, and S3 on the frame.

(3) If an alternating current is supplied to the rotor of a selsyn, the average magnetic field during a particular half-cycle is as shown in figure 266①. The total effect and direction of the field for this half-cycle are represented for convenience as the arrow in the simplified diagram of figure 266②. If the rotor is placed within the stator at *A* in figure 266③ and turned at the angle shown, the three coils are subjected to an alternating magnetic flux which induces voltages in the coils by means of transformer action. The voltages induced in coil 1 and coil 2 cause currents to flow in the direction shown by the arrows. No voltage is induced in coil 3 since it is cut by no magnetic flux, as it is perpendicular to the flux of the rotor. Assuming that the voltage generated in coils 1 and 2 is 45 volts, the voltage between the terminals of S1 and S2 is 45 volts plus 45 volts, or 90 volts as indicated. Similarly the voltage between the terminals of S2 and S3 is 45 volts plus 0 volts, or 45 volts, and between the terminals of S3 and S1 is 0 volts plus 45 volts, or 45 volts.

(4) By applying these three line voltages to the proper terminals of the stator of a second selsyn at *B*, the stator coils set up magnetic fields in the directions shown by the dotted arrows. The combination of the fields gives a magnetic field in the center of the stator at *B* which has the same direction and, because of losses, somewhat less magnitude than the original field produced by the rotor at *A*.

(5) Figure 266④ shows that a shift of rotor position at *A* produces different induced voltages in the coils of the stator. The flux of the rotor now induces equal but opposite voltages in coils 1 and 2; hence the line voltage between the terminals of S1 to S2 is zero. However, coil S3 has a maximum voltage, and therefore the voltages between S2 and S3 and between S3 and S1 both equal 78 volts. Again those voltages transferred to stator *B* produce a combined field which has the same direction as the rotor field in *A*, as shown by the dotted arrows. The same reasoning applies to the rotor position in figure 266⑤.

(6) The diagrams of figure 266 can be carried out for any rotor position. The results show that by means of the three varying line voltages there is a resultant magnetic field generated in *B* which always has the same direction as the original rotor field in *A*. Thus a mechanical motion of a shaft at *A* is transferred to a motion of a magnetic field at *B*. In order to transfer this stator-field motion back to

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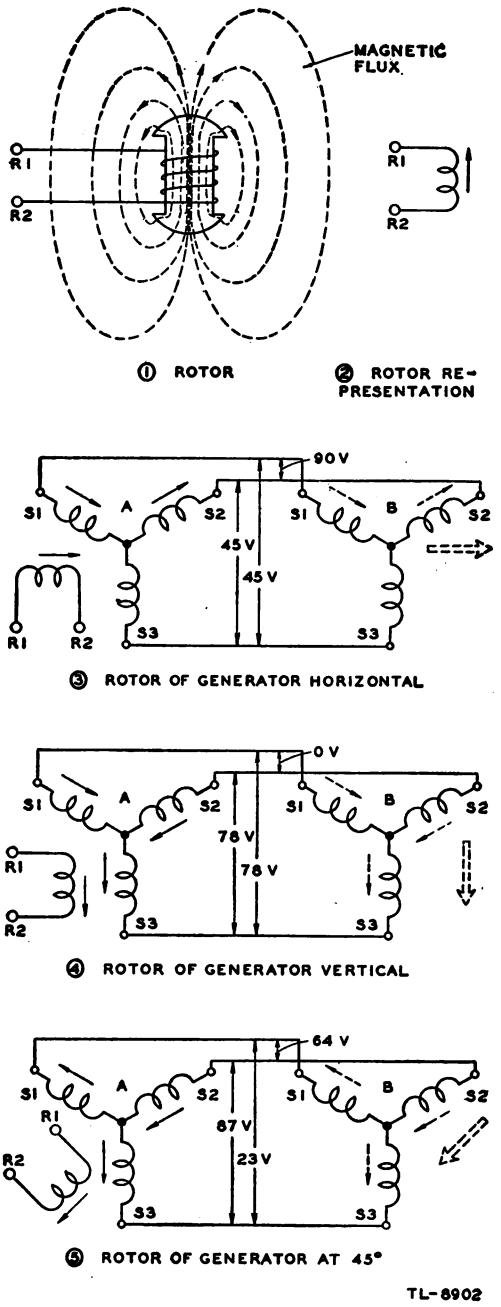

Figure 266. Selsyn principle.

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mechanical motion, it is necessary only to place another rotor at *B* which acts as an electromagnet and aligns itself with the stator field. The rotor fields must alternate in direction because the operation of the selsyn depends on the transformer action between rotor and stator. Since the rotor fields are alternating, they must always be in phase if the two selsyns are to keep in step. This is easily accomplished by connecting the rotor at *B* to the same a-c supply source as the rotor at *A*.

(7) Figure 267 shows a selsyn transmitter and receiver in a simplified diagram. Any motion of the shaft at *A* causes motion of the stator field at *B* and therefore a motion of the rotor shaft at *B* as the rotor attempts to follow the changing field direction. The twist or torque on the shaft depends on the angular difference between the stator and rotor field directions. So long as the rotor shaft at *B* is free to turn without any frictional drag or load, any slight movement of the stator field develops sufficient torque to cause the rotor to follow.

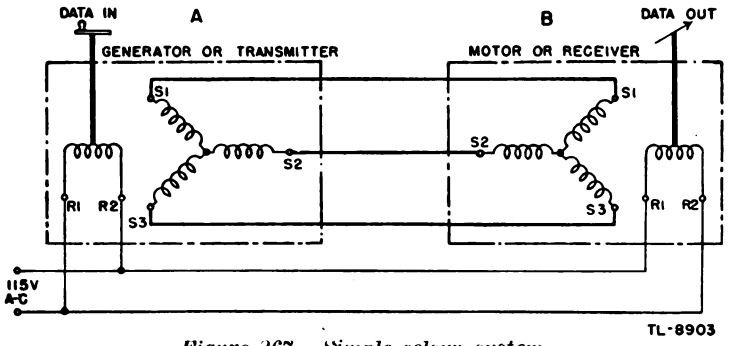

Figure 267. Simple selsyn system.

A selsyn designed for a freely turning rotor would probably overheat if the rotor were held fixed so that the angle between it and the stator field became greater than 20°.

(8) The transmitter selsyn *A* (fig. 267) is frequently called a selsyn generator, and the receiver selsyn *B*, a selsyn motor. Electrically, the selsyn generator and the selsyn motor are identical. Physically, they differ somewhat in that the motor has mounted on its rotor shaft an oscillation damper. This damper consists of a lead ring mounted within friction plates on a sleeve which is secured to the rotor shaft. The lead ring has a large amount of inertia and can be rotated on the sleeve only with considerable difficulty. Any violent oscillation of the rotor rotates the sleeve. The lead ring cannot follow this motion immediately because of its inertia, so that a large damping effect is produced on the oscillating rotor which quickly stops the movement. It should be noted that a selsyn generator does not necessarily rotate continuously as do most electrical generators, but may merely change its position by a few degrees. Similarly a selsyn motor may not rotate

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continuously, but follows in step with any movement of the selsyn generator. Currents in the three wires connecting the selsyn stators have their maximums at the same time, but vary in magnitude according to the rotor position. Therefore, the a-c voltages and currents in selsyns are single-phase.

(9) In radar applications the selsyn system in figure 267 is frequently used to transmit the antenna position. The input shaft of *A* is connected to the antenna turntable in such a manner that the position of the antenna in azimuth may be continuously transmitted to *B* which operates a dial and pointer at the operator's location some distance away. If the antenna can be tilted in elevation, a second identical selsyn system may be used to transmit the elevation angle as well.

(10) Some selsyn applications are made in which extremely accurate angular indication is desired. In such cases two selsyn systems

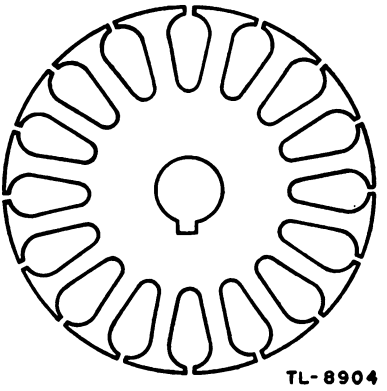

Figure 268. Rotor punching of differential sylsyn.

may be used, one directly coupled to the shaft from which position information is desired and the other coupled through a gear ratio of, for example, 36 to 1, so that the selsyn generator makes 36 revolutions to 1 of the antenna shaft. The antenna position then is given on two dials. The coarse reading is given by the first selsyn system and the fine reading by the second. The fine-reading pointer makes one complete revolution for each 10° angular movement of the antenna. The disadvantage of such a system is that the two selsyn systems may be turned out of step when the power is off, so that the 36-speed system may synchronize at some multiple of 10° out of step when power is again applied. Certain special circuits and devices have been developed to remedy this disadvantage by producing a combination coarse and fine system which is completely self-synchronizing.

b. Differential selsyns. (1) The differential selsyn is similar to the basic selsyn except that the rotor has, instead of a single

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coil, a three-coil winding similar to that on the stator. The rotor core, therefore, is slotted to accommodate the distributed windings (fig. 268). The position of the rotor field flux with respect to the stator is then determined by two factors: the mechanical position of the rotor shaft, and the electrical position of the field flux within the rotor itself as determined by the three rotor input voltages. The differential selsyn is designated as generator or motor, the only difference being the addition of a damping device on the motor shaft. The differential selsyn is used where the receiving selsyn is to be controlled by two or more transmitting selsyns.

(2) A control or indicator system in which a differential selsyn generator is used is shown in figure 269. The positions of the rotors of the generator and of the differential generator are controlled by the connected apparatus, and the algebraic sum of the effects of these two machines determines the position of the rotor of the motor. The

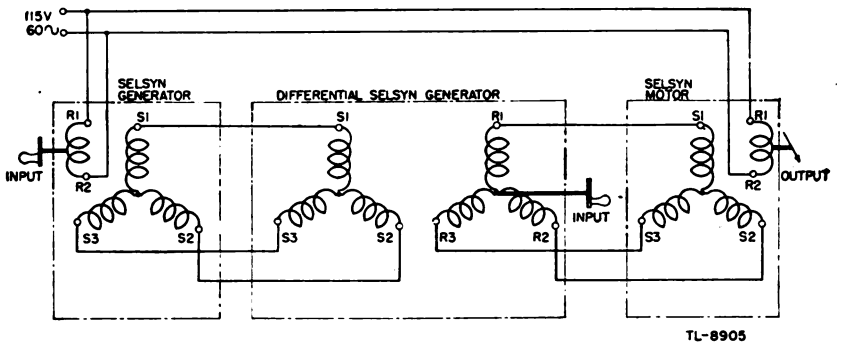

Figure 269. Control or indicator system using differential selsyn generator.

stator of the differential generator is energized by the output from the stator of the selsyn generator, so that axes of the stator fields of these two machines are always in the same direction. The voltages induced in the rotor of the differential selsyn determine the direction of the stator field of the motor, and hence the position of the rotor.

(3) If the system is at rest and all rotors are free to turn, all the rotors will be at the zero position (fig. 270). If the rotor of generator *G* is turned 60° clockwise while the rotor of differential selsyn generator *DG* is held fixed, the stator field of *G* is rotated through the same angle (fig. 271), causing the stator field of *DG* also to be rotated 60°. The voltages induced in the rotor of *DG* are now such as to cause the stator field of motor *M* to be as shown, so that the rotor of *M* turns 60° clockwise. The same effect can be produced by holding the rotor of *G* fixed and turning the rotor of *DG* counterclockwise (fig. 272,) since this rotation causes the same relative shift

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between the axis of the rotor and the direction of stator field of *DG* as was made in the first case.

(4) If the rotors of both *G* and *DG* are turned 60° clockwise, there is no change in the voltages induced in the rotor of *DG* because there is no relative shift between the axis of the rotor and the direction of

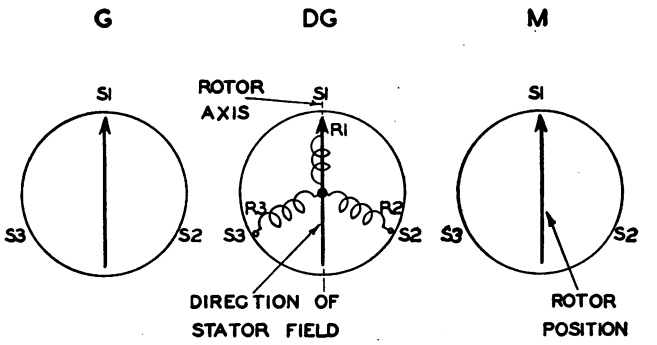

Figure 270. Zero position of selsyn system.

the stator field of *DG* (fig. 273). As a result, the rotor of *M* remains at zero.

(5) Thus, the effect of the differential selsyn in the control system is to cause the motor to turn through an angle which is equal to the

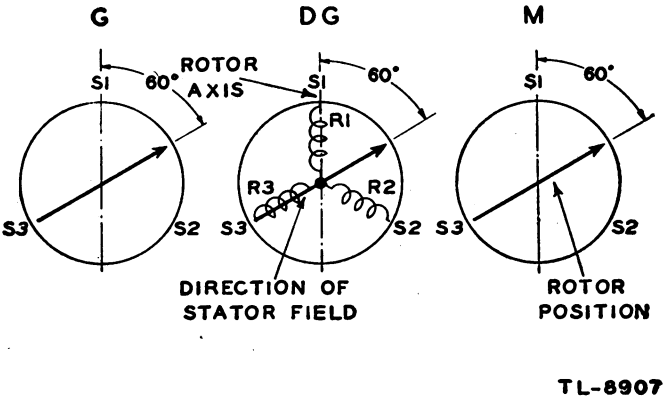

Figure 271. G rotor turned 60° clockwise, DG rotor held at 0°.

relative shift between the axis of the rotor and the direction of the stator field of the differential generator. Two further examples of the action of the differential generator are shown in figure 274① and ②. In ① the rotor of the generator is turned 45° clockwise and the rotor of the differential generator is turned 30° counterclockwise. As a

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result, there is a clockwise shift of 75° between the axis of the rotor and the direction of the stator field of *DG*, which causes the rotor of *M* to turn 75° clockwise. In ② both rotors are turned counterclockwise so that the effects of the two motions subtract. Thus, the rotor of the motor turns only 15°, which is less than the motion of either of the other machines.

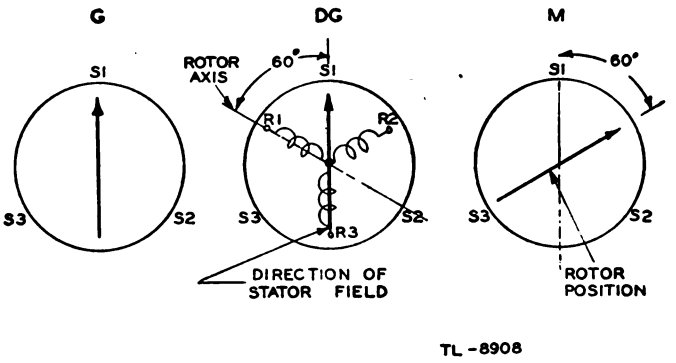

Figure 272. G rotor held at 0°, DG rotor turned 60° counterclockwise.

(6) It should be noted that the effect of the differential generator in the circuit may be reversed by exciting the *DG* rotor from the selsyn generator instead of the stator as in figure 269. In this connection the *DG* rotor must be turned clockwise in order to neutralize a counterclockwise motion of the *G* rotor.

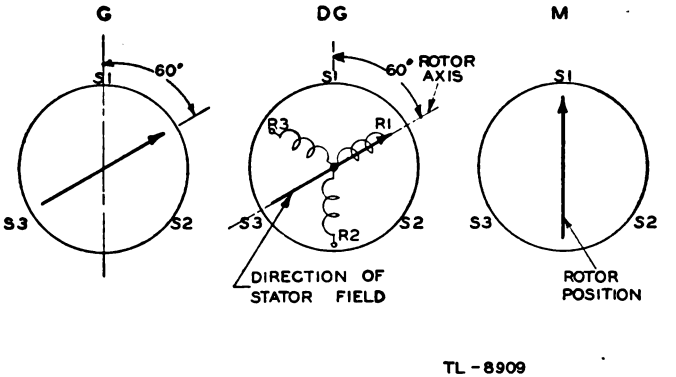

Figure 273. G rotor and DG rotor both turned 60° clockwise.

(7) A control or indicator system in which the output is taken from the shaft of the differential selsyn may be built by replacing the motor in figure 269 with a generator, and by making the differential machine a motor (fig. 275). The two end selsyns have shafts positioned by equipment. The rotor shaft of the differential selsyn trans-

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mits the desired information, which is the sum or difference of the other two rotor-shaft positions.

(8) Figures 269 and 275 show that the differential selsyns are supplied with power from a selsyn generator. For this reason the selsyn generator used with differential selsyns may be of heavier design to prevent overheating. Such machines are called *exciter selsyns.* In

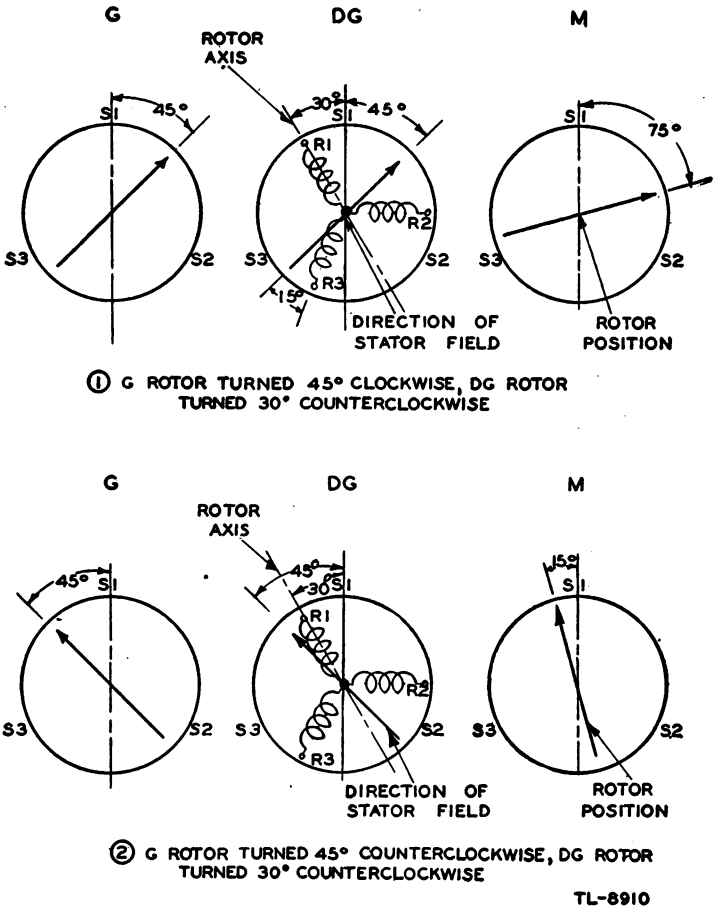

Figure 274. Sum and difference motion produced by action of differential generator.

the case of complex systems involving several differential selsyns, capacitors may also be placed across the leads to the differential selsyn stator to counteract the lagging excitation current. Where lines between selsyns are long, this practice reduces voltage drops and power losses which may become an appreciable part of the total power consumed.

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e. Selsyn control transformer. (1) Although different in application, a selsyn control transformer is essentially the same in construction as a selsyn generator (fig. 276). In the control transformer the rotor is held fixed, either by being attached to a shaft or by being clamped to the frame of the selsyn itself. The rotor winding, then,

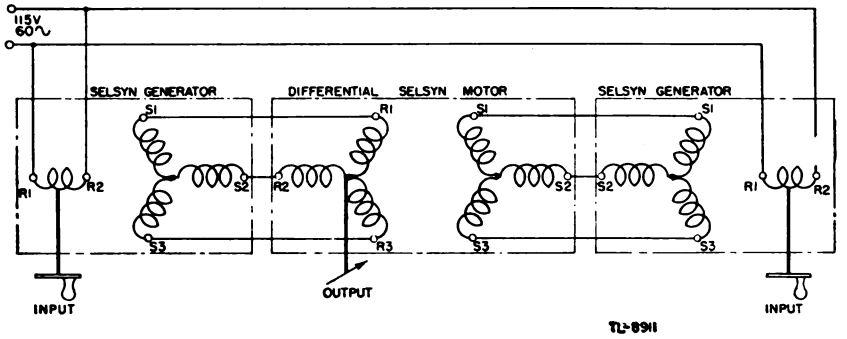

Figure 275. Indicator system with two controlling shafts and one controlled shaft using differential selsyn motor.

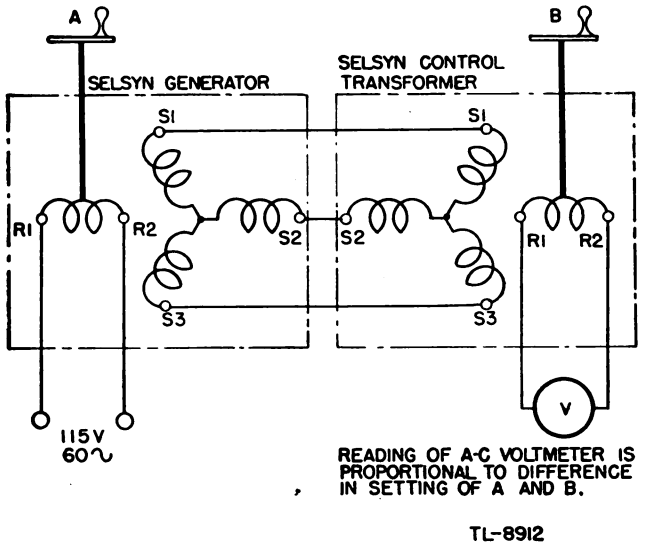

Figure 276. Selsyn control transformer circuit.

instead of being supplied by the a-c line, supplies to an amplifier or meter an alternating voltage which varies with the angle between the stator field and the axis of the rotor.

(2) The control transformer is used to produce an *error* voltage for control purposes in servo systems, since this transformer produces a voltage proportional to the discrepancy between the stator field position and the mechanical position of the rotor.

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d. Potentiometer systems. One of the simplest methods of data transmission is to use a potentiometer the resistance of which is varied by the rotation of the antenna. The indication may be obtained by the reading of a meter (par. 24e(5)) or the output of the potentiometer may be used to give the azimuth or elevation sweep of a type B- or C-scan oscilloscope.

60. WARD-LEONARD SYSTEMS.

a. Ward-Leonard drive. (1) In radar applications it frequently is necessary to drive heavy rotary equipment at varying

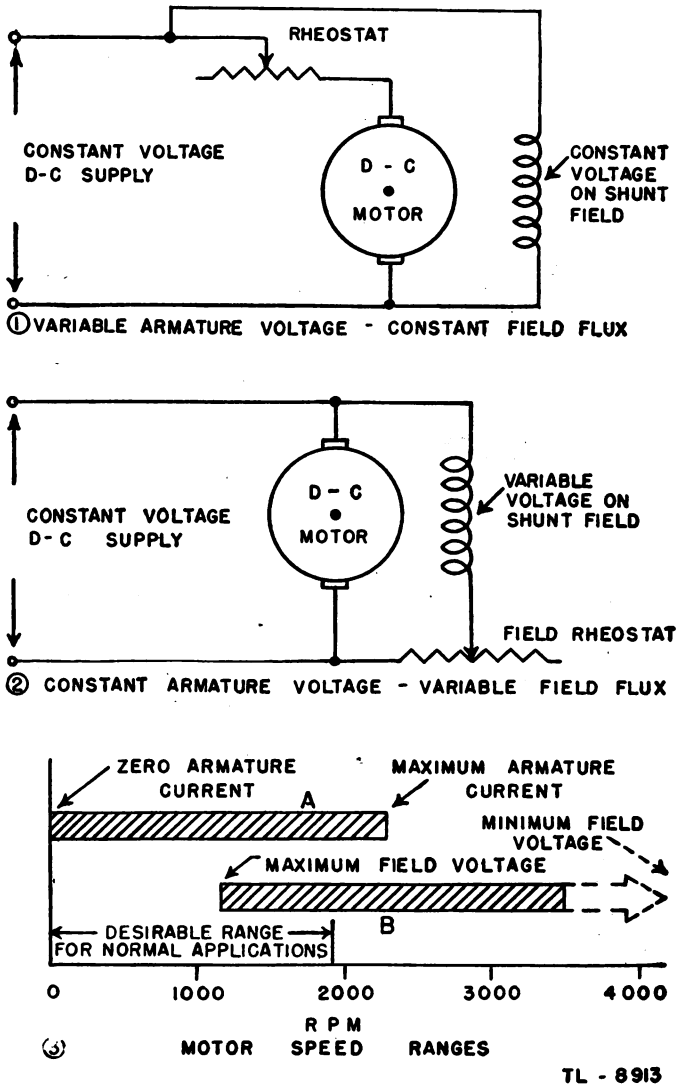

Figure 277. Basic speed control of d-c motors.

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speeds and in either direction of rotation, and in most cases to maintain remote control over such drives. Since the ordinary single-phase or three-phase a-c motor is inherently a constant-speed device, the direct current motor is commonly used for controlled drives. The direction of rotation can be changed readily by reversing either the armature current or the field current but not both.

(2) The speed can be controlled by at least two methods; either the voltage on the armature can be varied as in figure 277①, or the field voltage can be varied as in figure 277②. The first method gives the most stable control and the most desirable range of speed (fig. 277①), but if a variable resistor is used in series with the armature, heavy power losses will occur, especially in the larger motor sizes. The second method permits control with a physically smaller

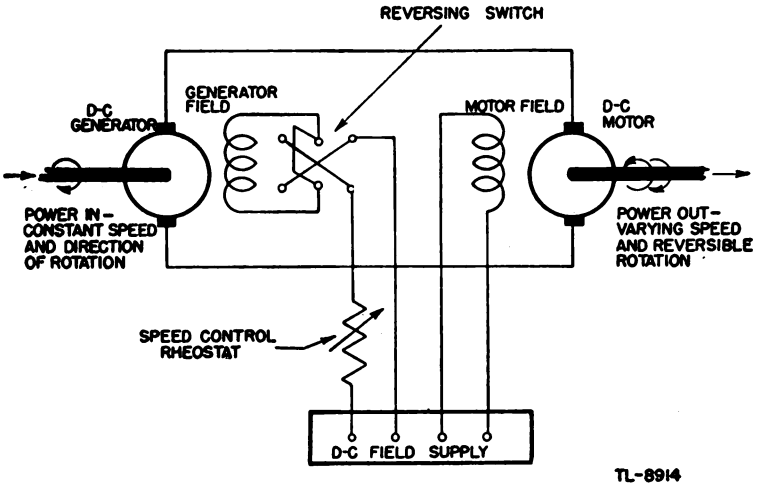

Figure 278. Ward-Leonard drive.

resistor and greatly reduced power losses, but the available motor speeds range from a certain minimum value upward (fig. 277②), rather than from a certain maximum value downward to zero as is desired (fig. 277③). The motor will also be relatively unstable in its higher speed ranges since the field is very weak.

(3) One solution to the problem is to use the circuit of figure 277① but to replace the resistor with a voltage reducing device which will have comparatively low power losses. The circuit shown in figure 278, commonly known as the Ward-Leonard system, accomplishes this result. The d-c motor in this circuit is fed directly from a d-c generator which is operated at a constant speed. The d-c field supply to the generator is variable in both magnitude and polarity by means of a rheostat and reversing switch as shown. Therefore, the motor armature is supplied by a generator having smoothly

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varying voltage output from zero to full-load value. The motor field is supplied with a constant voltage from the same source as that supplying the generator fields. The generator drive power could be from a single-phase or three-phase a-c motor, from an engine, or from any other constant speed source. In the same way the d-c field supply can be supplied from a rectifier, from an exciter on the end of the generator shaft, or from any other suitable d-c source.

b. Application of basic Ward-Leonard drive. (1) The advantage of the Ward-Leonard system is that by means of the variation of a small field current a smooth, flexible, yet stable control can be maintained over the speed and direction of rotation of a d-c motor. Such systems are applicable to ship propulsion, hoists and elevators, Diesel electric equipment, and to the rotation of gun turrets, radar antennas, and similar heavy equipment. The action of the system is very much like that of an amplifier since a very small amount of power is used to control greatly increased power.

(2) A simple Ward-Leonard drive for a radar antenna is shown in figure 279. The d-c generator in this system is driven by a 230-volt single-phase a-c motor. The same a-c line supplies a rectifier which furnishes field supply for both the d-c generator and the d-c motor fields. However, the generator field is connected to a potentiometer in such a way that the magnitude and polarity of the applied voltage can be varied. By varying the setting of the potentiometer control knob, the antenna can be rotated in either direction and at any speed from zero to full rate.

(3) In practical installations the motor generator set at *A* could be at any convenient location. The drive motor at *B* would be on the antenna tower at the base of the rotary antenna mount. The control box *C* would be located near the operator and the rectifier *E* would probably be near or in the control box.

c. Ward-Leonard servo system. (1) The basic Ward-Leonard system has a number of limitations when applied to antenna control for radar systems. As a rule, it is desired to control the direction in which the antenna points. The antenna may be required to rotate continuously for normal searching or to be turned only a few degrees in azimuth in order to determine the bearing of a target. Where the antenna is large, the driving system should be capable also of supplying sufficient power to make the antenna rotate in step with the controls in spite of varying wind pressure. The adaptation of the Ward-Leonard drive to the servo system shown in figure 280 satisfies the requirements of a radar antenna control system.

(2) The a-c driving motor, d-c generator, and the antenna drive motor in figure 280 make up the fundamental Ward-Leonard drive. The field supply for both the antenna drive motor and the d-c genera-

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tor is obtained from an exciter, a small self-excited d-c generator which also is driven by the a-c driving motor.

(3) The field supply voltage for the d-c generator is obtained from a Wheatstone bridge made up of R1, R2, R3, and R4. If the resistance

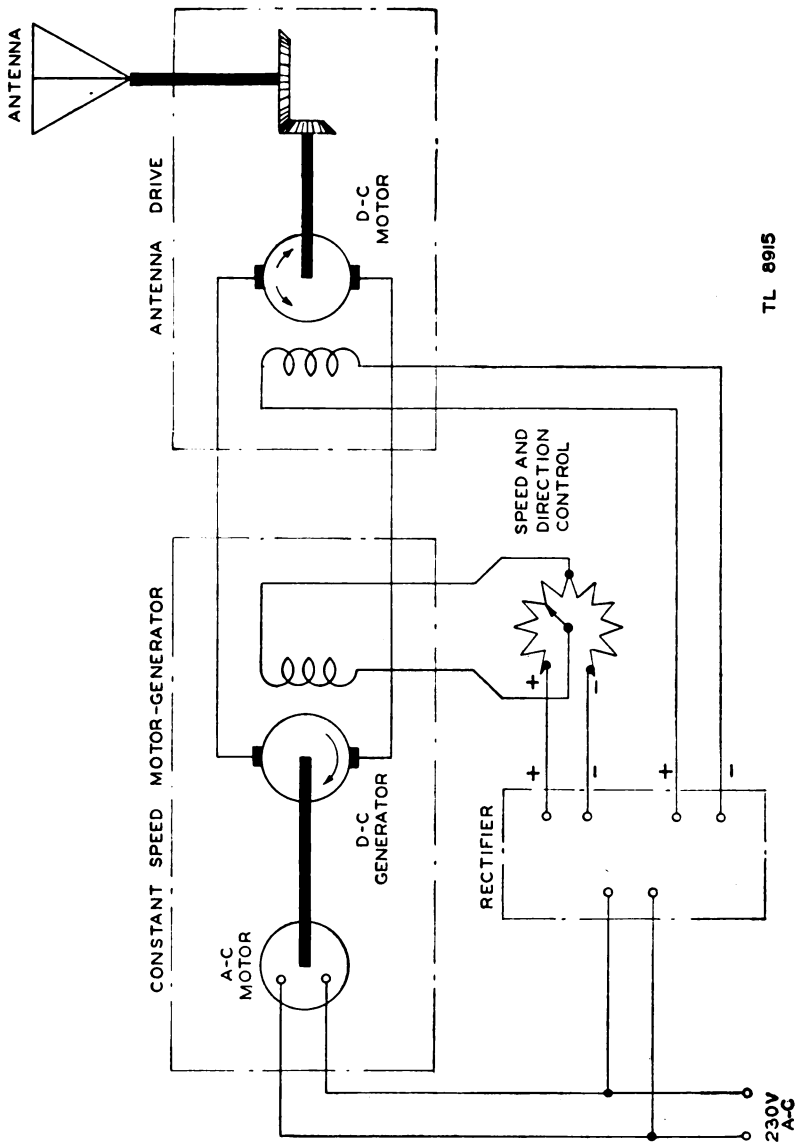

Figure 279. Simple radar antenna drive.

of R1=R3 and R2=R4, the bridge is balanced and the voltage between points *A* and *B* is zero. In this condition, the output of the d-c generator is zero, so that the antenna driving motor is stopped. However, if the resistance of R1 is decreased by short-circuiting part of the

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resistor, the bridge becomes unbalanced, making point A positive with respect to point B. The voltage across AB is impressed on the field of the d-c generator, causing the antenna drive motor to rotate. The speed at which the drive motor rotates is dependent on how much the

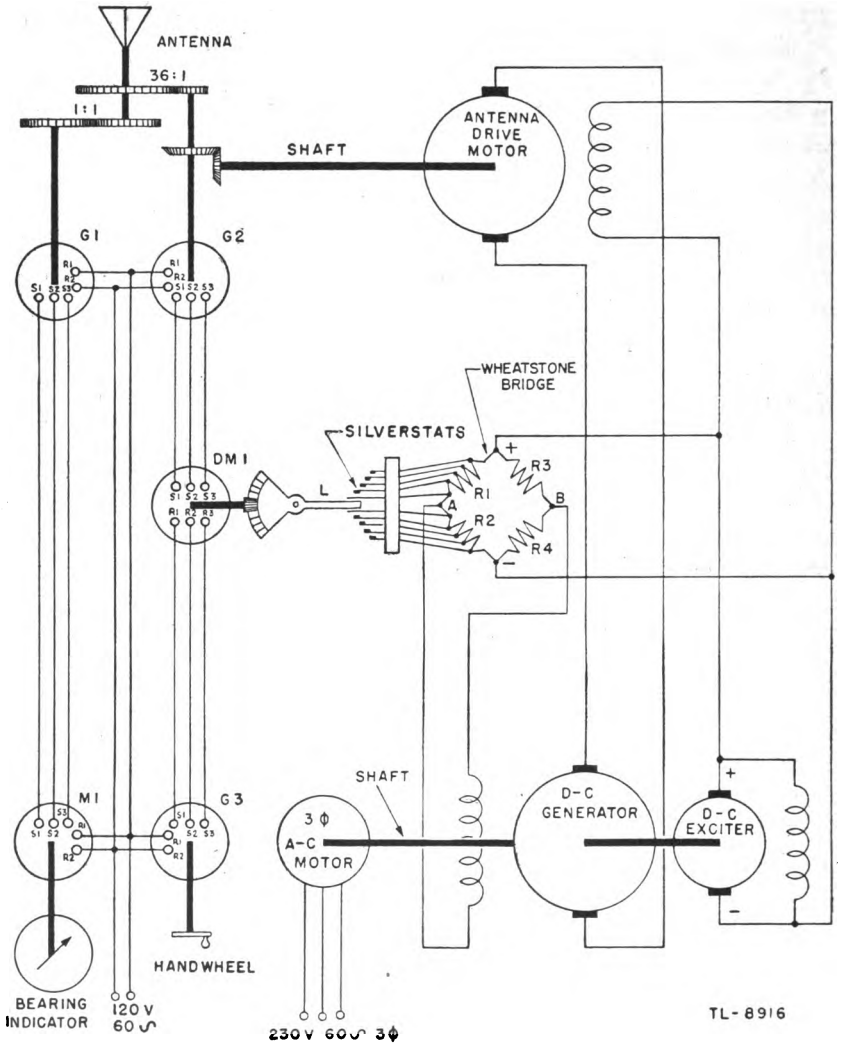

Figure 280. Ward-Leonard servo system for antenna control.

resistance of R1 is reduced. The antenna may be made to rotate in the opposite direction by reducing the resistance of R2.

(4) Resistors R1 and R2 are tapped at several points which are connected to a pair of Silverstat contractors as shown. The resistance of either R1 or R2 is reduced by an amount dependent on how many

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contacts are closed. The Silverstats are operated by a lever arm, *L*, which is geared to a differential selsyn motor. Thus, the speed and direction of rotation of the antenna are determined by the lever arm which controls the voltage impressed on the d-c generator field.

(5) When the antenna is stopped, the rotor of DM1 is in a neutral position such that no contacts on either Silverstat are closed, and the Wheatstone bridge is balanced. If the handwheel on the rotor of selsyn generator G3 is turned, the voltages induced in the stator will change. Since the rotor of the differential selsyn motor is energized from the stator of G3, the rotor of DM1 turns when the handwheel is turned. The rotation of DM1 causes a deflection of the lever arm by the connection through bevel gears. This deflection causes the Silverstat to change the resistance of either R1 or R2, so that the d-c generator produces a voltage which causes the drive motor to turn the antenna in the same direction that the handwheel was turned. Since the rotor of selsyn generator G2 is geared to the antenna drive motor, the rotation of this motor changes the output from the stator of G2. This change in output causes a rotation of the stator field of DM1 which tends to bring the rotor of this machine to its neutral position.

(6) Thus, if the handwheel is turned only 10°, the antenna will turn only 10° and stop. However, if the handwheel is turned continuously, the antenna will turn continuously because the rotor of DM1 is kept out of its neutral position by some constant small angle. This small angle, or error, is relatively large if the handwheel is turned fast so that the antenna will also turn fast; the error is small if the handwheel is turned slowly.

(7) The position of the antenna may be indicated at a distance by the use of the selsyn system made up of G1 and M1. If desired, selsyn generator G1 may feed signals to several selsyn motors to indicate the antenna position at several places simultaneously.

(8) In an actual antenna-control system, hunting may occur because the inertia of the antenna may cause it to overshoot the desired position. If it does so, the voltages in the stator of G2 cause the lever arm to be displaced from its neutral position in a direction opposite to the displacement which caused the rotation. The overshooting causes the drive motor to reverse, and again the inertia of the system may cause it to overshoot, but in the other direction. Thus, overshooting develops a small error signal which causes the whole system to oscillate about the desired position. The amplitude of the oscillation is insufficient to interfere with the operation of the radar set, but the mechanical vibration set up by the hunting can cause failure of the antenna system.

(9) The lever arm which operates the Silverstat in the Ward-Leonard servo system may be modified by the addition of a gyroscope (fig. 281)

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to reduce the hunting of the system. The gyroscope and its driving motor are mounted as a unit in trunnions on the lever arm. The position of the gyroscope relative to the lever arm is fixed in the static condition by a pair of balancing springs. Projection *A* on the gyroscope assembly operates the contacts of the Silverstat in a manner similar to the action of the lever itself in figure 280.

(10) The rotor of the gyroscope is turned at high speed by the drive motor. By virtue of its great momentum, the gyro rotor tends to remain fixed in space. If the lever arm is turned about its pivot, the gyro tends to precess, or rotate, about the axis through the trunnions.

(11) The over-all action of the servo system is the same whether

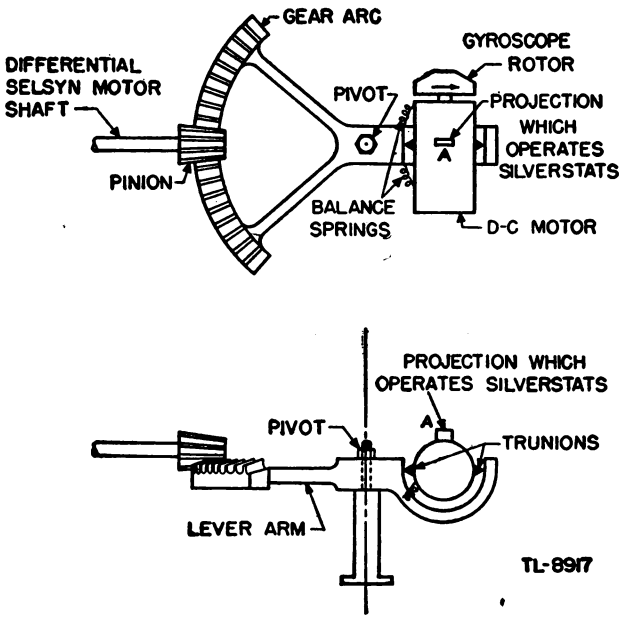

Figure 281. Gyroscope antihunt system.

the gyroscope is used or not, but the gyro tends to eliminate hunting and to increase the speed of response to the controls. For example, if the handwheel is turned suddenly, the rotor of DM1 immediately tends to turn to a new position. The sudden motion of the lever arm moves *A*, which unbalances the Wheatstone bridge by the operation of the Silverstat. In addition the gyroscope precesses about its trunnions, causing a further motion of *A* in the same direction, which further unbalances the bridge. Thus any sudden change of the controls causes high acceleration of the antenna-drive motor because of the additive effect of the precession of the gyro.

(12) As the antenna rotates and the "error" in the field positions within DM1 decreases, the geared lever arm turns back toward its

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neutral position. The gyroscope is pulled to its normal position by the balancing springs, and then it precesses in the opposite direction as the lever arm moves toward neutral. This tilting reduces the unbalance of the Wheatstone bridge by pulling *A* back toward neutral more quickly than is possible with the lever arm alone, causing the antenna-drive motor to slow down as the antenna approaches the desired position. This action tends to prevent the antenna from overshooting or from oscillating about the desired position. Thus, the action of the gyroscope is to cause the antenna-drive motor to be accelerated rapidly to start the antenna turning, and to cause the antenna to approach a desired position slowly to prevent hunting.

d. Electronic control of Ward-Leonard servo system. (1) The control function may be performed electronically in a servo system using the Ward-Leonard drive. In such a case, the differential selsyn, gyroscope, Silverstat, and Wheatstone bridge of figure 280 can be replaced with a selsyn control transformer and an electronic emplifier which converts the selsyn a-c voltage to direct current of sufficient power to control the d-c generator field in the Ward-Leonard drive.

(2) Figure 282 is a block diagram of this type of system. The position of the handwheel and rotor of the selsyn generator G2 determines the position of the field in the stator of the selsyn control transformer. No voltage is induced in the rotor of CT1 if it is at right angles to the stator-field flux. However, if the rotor is in any other position, a voltage is induced in its windings, which is fed to the control amplifier. The output of the amplifier causes the antenna to be rotated so that the rotor winding of CT1 is turned to a position at right angles to the stator field flux. Therefore, the voltage no longer is induced in the rotor of CT1, and the antenna driving power is reduced to zero.

(3) The direction rectifier is a circuit in which the phase of the error voltage output of the control transformer is compared with a *reference voltage* to determine the polarity of the control amplifier output. If the two voltages are in phase, the antenna is turned in one direction; if the two voltages are 180° out of phase, the antenna is turned in the other direction. The amplitude of the output of the control transformer determines the magnitude of the voltage applied to the field of the d-c generator, and therefore the speed of the antenna-drive motor.

(4) The feedback circuit acts to prevent hunting by reducing the amplifier gain as the voltage on the control motor decreases, thus causing a further decrease of voltage to the motor. In this way, the rate of antenna rotation is rapidly reduced as the desired position is reached, and the antenna is prevented from over-traveling.

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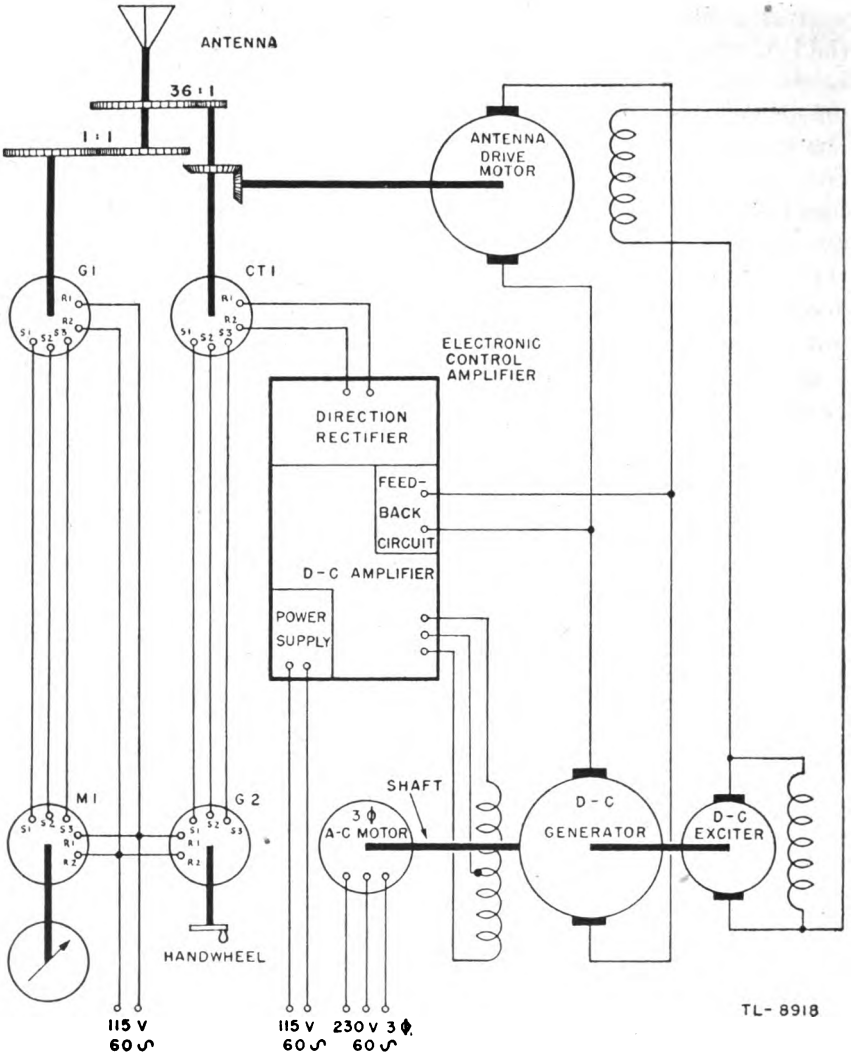

Figure 282. Electronic control of Ward-Leonard servo system.

61. AMPLIDYNE SERVO SYSTEMS.

a. Amplidyne generator. (1) The amplidyne drive is similar to the Ward-Leonard drive (par. 60) except that a special d-c generator called an *amplidyne* (a trade name) is used in place of the regular d-c generator. The principal difference between the amplidyne and the ordinary generator is that the field of the amplidyne requires a much smaller amount of control power for the same values of output power. In other words, the amplidyne functions

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as an electro mechanical power amplifier in which the amplification is very much greater than in the Ward-Leonard generator.

(2) The ordinary generator can be regarded as a one-stage amplifier as shown in figure 283①, in which a small power input to the field controls a large power at the output terminals. The additional power supplied to the generator shaft by an engine or motor in this case corresponds to the power supplied to the plate of a vacuum-tube amplifier. In order to increase the amplification the output of one generator may be used to supply the control field of a second machine, as in figure 283②. This arrangement acts, in effect, as a second stage

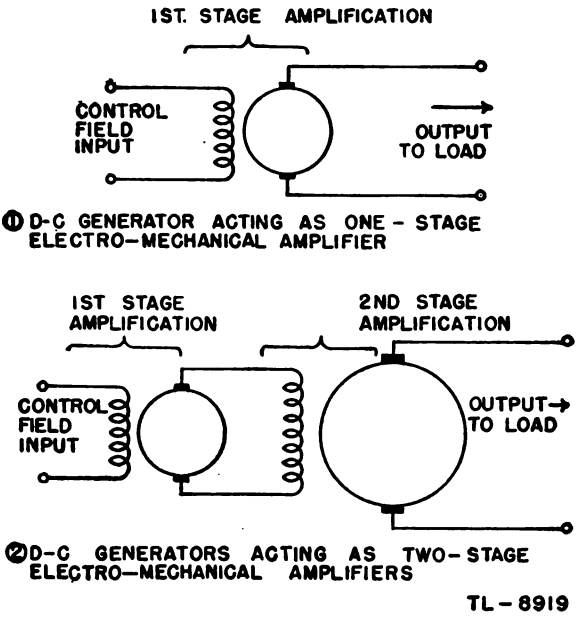
1ST. STAGE AMPLIFICATION
CONTROL FIELD INPUT
OUTPUT TO LOAD
① D-C GENERATOR ACTING AS ONE - STAGE ELECTRO-MECHANICAL AMPLIFIER
1ST STAGE AMPLIFICATION
2ND STAGE AMPLIFICATION
CONTROL FIELD INPUT
OUTPUT TO LOAD
② D-C GENERATORS ACTING AS TWO-STAGE ELECTRO-MECHANICAL AMPLIFIERS
TL-8919

Figure 283. Generators as electromechanical amplifiers.

of amplification and the total power gain of the system is the gain of the first stage multiplied by that of the second. The Ward-Leonard generator may be compared to ① and the amplidyne to ②. However, instead of having two separate armatures, the amplidyne has been designed to incorporate both stages of amplification into the one armature.

(3) Figure 284 shows the magnetic fields in a conventional d-c generator supplying a load current of 100 amperes. The field current required to create the necessary excitation flux may be in the neighborhood of 5 amperes. Because of this flux, labeled ϕ_e in the drawings, there is a north pole in the machine frame at the left and a south pole in the frame at the right. Since the armature current of 100 amperes

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also flows through turns of wire on an iron core, the armature itself becomes an electromagnet. Magnetic flux generated in this matter is termed armature reaction flux and is shown in figure 284① by the flux loops labeled ϕ_a. If the direction of the current in the armature

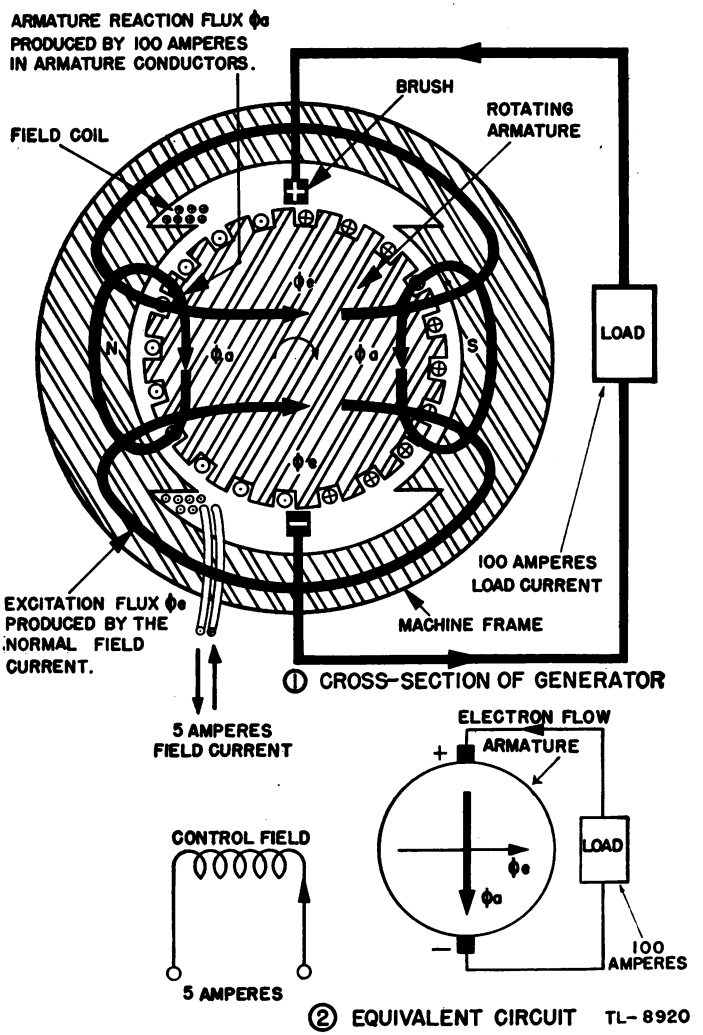

Figure 284. Magnetic fields in conventional d-c generator.

conductors is considered, it is evident that the armature reaction flux is at right angles to the excitation flux as in figure 284②.

(4) If the external load is removed from the armature circuit and a short circuit is connected across the brushes (fig. 285), the excitation or control field current must be reduced greatly to prevent damage to the generator because of excessive armature current. The only

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resistance in the armature circuit in this case is that of the armature conductors, of the brushes, and of the short-circuit connection. Therefore, only a very small voltage need be induced in the armature to produce 100 amperes in the armature circuit, and the control field current must be reduced from 5 amperes to perhaps as low as $\frac{1}{20}$

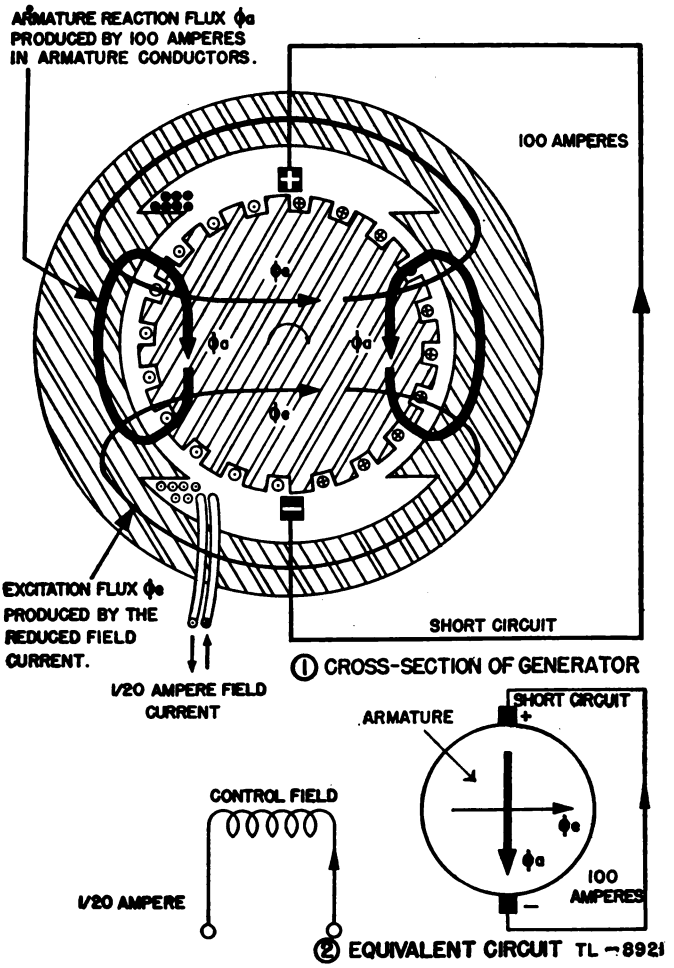

Figure 285. Magnetic fields in short-circuited d-c generator.

ampere. Figure 285① shows the magnetic fields set up in a short-circuited d-c generator. If the armature current is limited to 100 amperes by reducing the control field, the magnitude and direction of the armature reaction flux are the same as in the loaded generator of figure 284, but the control flux is very small. The currents that flow in the armature conductors because of the short circuit are such that the armature reaction flux remains fixed in space, just as though

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the armature were a stationary coil with its axis at right angles to the axis of the control field windings.

(5) Since the armature conductors are uniformly distributed about the armature, it is evident that some of these conductors will cut across the reaction flux at the same rate as others cut across the excitation flux. However, because of the location and direction of the two magnetic fields, the maximum voltage caused by the cutting of the reaction flux appears across the armature at right angles to the voltage developed by the excitation flux. Therefore by placing a second set of brushes at right angles to the short-circuited brushes (fig. 286), sufficient voltage is available to supply another 100 amperes to an external load, in addition to the 100 amperes flowing through the short-circuited path. Since the control field flux has to build up only to a low value and since the resistance of the short-circuited armature is very small,

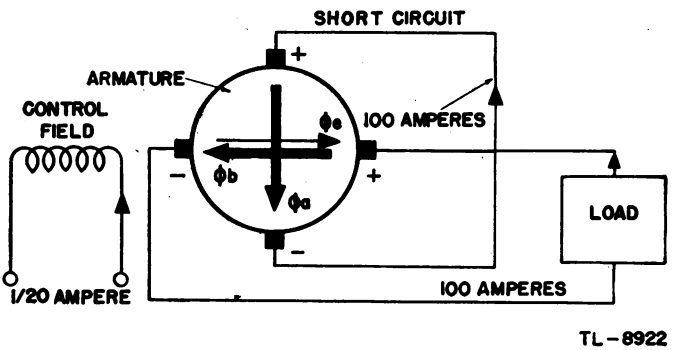

Figure 286. Addition of second pair of brushes to short-circuited d-c generator.

full-load current may be obtained in an exceptionally short time. Thus changes in the control-field current are amplified almost instantaneously by the amplidyne.

(6) However, the direction of the load current is such that it produces a second armature reaction flux (ϕ_b in fig. 286) which is at right angles to the short-circuit armature reaction flux ϕ_a, and in direct opposition to the original control flux ϕ_e. The load armature reaction flux will be much greater than the control flux, and would prevent the control field current from controlling the output. It is very important that the small control flux not be affected by the armature reaction if it is to retain control over the output. Therefore a series compensating winding through which the load current flows is wound around the control-field poles. The number of turns in this winding usually is adjusted so that the compensating flux (ϕ_c in fig. 287) exactly cancels the load armature reaction flux for all values of load current in the operating range. In this case, the effective magnetic fields are as shown in figure 288. If the compensating flux is slightly under the value for

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complete neutralization, the machine has reduced power gain and acts as a degenerative amplifier; however, the operation may be somewhat more stable. Overcompensation, on the other hand, creates the effect of regenerative amplification, and the operation of the machine may easily become unstable.

(7) Since any residual magnetism along the axis of the control field would have a large effect on the amplidyne output, it is necessary to demagnetize the core material. This demagnetization is accomplished

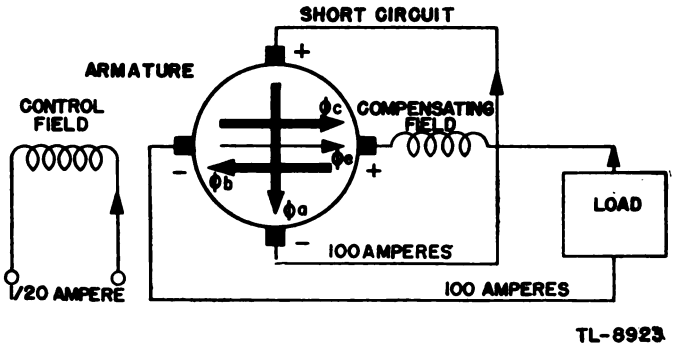

Figure 287. Addition of compensating winding to short-circuited d-c generator.

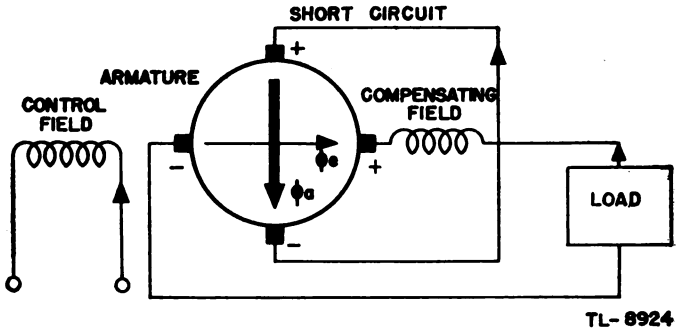

Figure 288. Effective magnetic fields in amplidyne.

by attaching an Alnico magnet on the end of the armature. The magnet revolves within a separate field winding and generates a small a-c voltage which is applied to two sets of opposed windings on the field poles (fig. 289). Thus the generated alternating current neutralizes any residual magnetism when the control-field current is zero. The effect of this demagntizing system is similar to that created by an a-c coil used to demagnetize watches.

(8) Returning to the diagram of figure 283②, it may be noted that the production of the short-circuit current and its associated armature reaction flux by a small control field represents the first stage of am-

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plification, which can be regarded as principally current amplification. The use of this large current and the flux it produces to induce sufficient voltage to drive an equally large current through the external load circuit represents the second stage, which can be regarded as essentially voltage amplification. The compensating winding, in addition, can be regarded as a feedback circuit, where exact compensation corresponds to zero feedback. The power gain of an amplidyne may range from 3,000 to 10,000 and perhaps higher in certain machines. This is in contrast to the gain of ordinary generators which will likely be in a range of from 25 to 100.

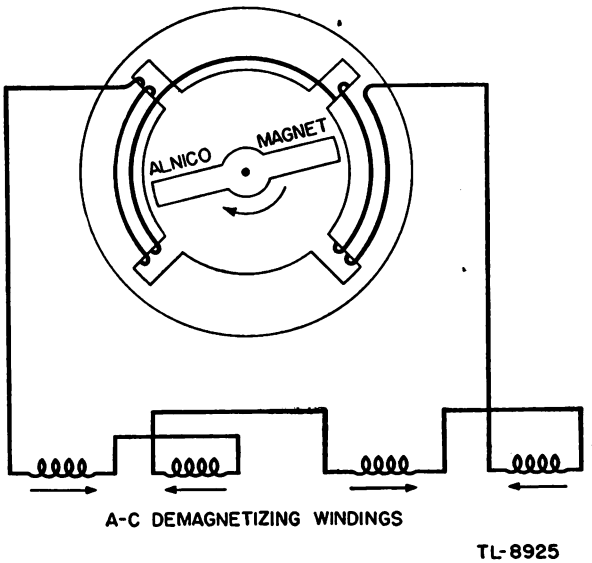

Figure 289. Demagnetizing windings for amplidyne generator.

b. Amplidyne drive. (1) The amplidyne drive as commonly used consists of the basic system as shown in figure 290. Note that the symbol used for the amplidyne generator is similar to that of the conventional d-c generator, except that an extra set of brushes connected by a curved shorting bar has been added. The amplidyne generator is ordinarily driven by an a-c motor. The control field is shown as a split winding, as it is common to supply the fields by means of a control amplifier having separate outputs for each polarity of the applied signal. The series compensating winding is usually omitted from schematic drawings to avoid complication. The field of the d-c motor can be supplied by a rectifier or by a pair of permanent magnets. In motors having a permanent-magnet field the heavy armature current creates a large armature reaction flux which tends to demagnetize the permanent magnets. To prevent this demagnetization, compen-

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sating windings are connected in series with the armature and wound on the faces of the field poles to neutralize the armature reaction flux.

(2) Figure 291 shows the basic type of control amplifier which is ordinarily used to supply the amplidyne control field. Such an amplifier is controlled by comparing an a-c *error voltage* from a selsyn con-

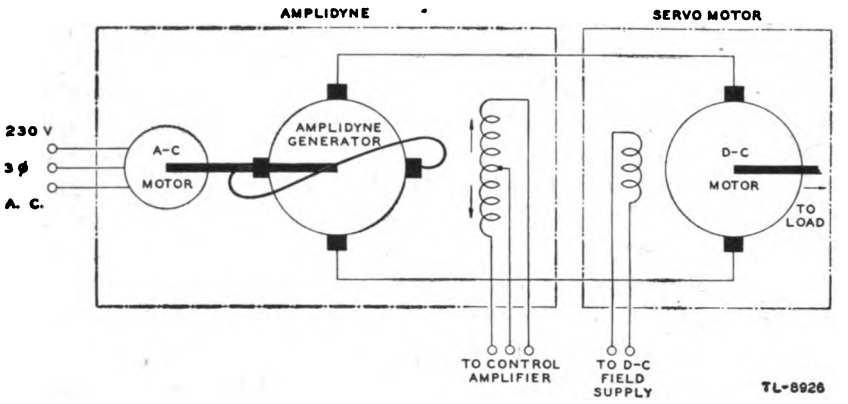

Figure 290. Basic amplidyne drive.

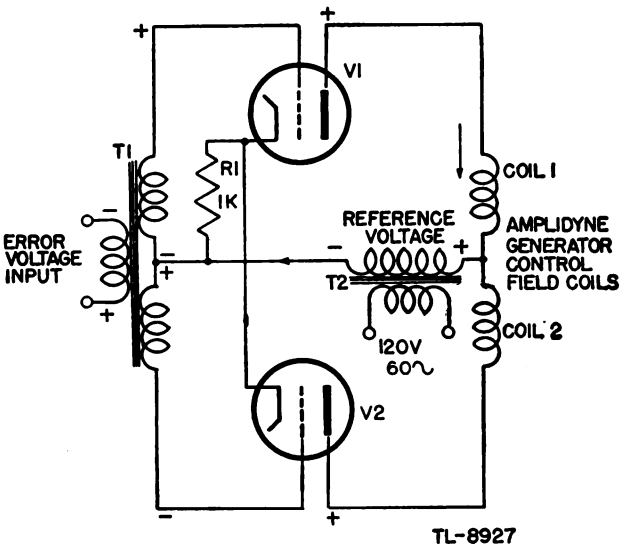

Figure 291. Basic amplidyne control amplifier.

trol trasformer to an a-c *reference voltage* furnished by the a-c line supply. Actually the 110-volt, 60-cycle, a-c line supplies both of the transformer inputs, but the error voltage input to T1 may be varied in magnitude or reversed in phase with respect to the reference voltage input of T2 by means of the selsyn transformer. The polarity signs are shown for a particular instant. It is assumed that there is

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no phase-shift and therefore both a-c input voltages are in phase. The plates of both tubes are positive, but the grid of V2 is below cut-off, and the grid of V1 is above cut-off. Therefore, electron flow is as shown by the arrows from V1, and the field coil 1 is energized. On the next half cycle the plates are both negative and no current flows regardless of the grid voltages, which have also reversed. Thus the output is that of a half-wave rectifier supplying coil 1; coil 2 is inoperative.

(3) If the phase of the voltage input to grid transformer T1 is shifted 180°—that is reversed—while the phase of the a-c line input remains the same as before, the circuit acts as a half-wave rectifier for coil 2, and coil 1 is inoperative. If the two coils are both wound on the amplidyne field poles, but in opposite directions, a 180° shift in a-c grid voltage changes the direction of the control field flux and hence changes the polarity of the amplidyne output. The magnitude of the amplidyne output is thus controlled by the magnitude of the a-c error voltage, and the polarity by the phase of the error voltage.

c. Application of Amplidyne Drive to Servo System. (1) The basic amplidyne drive (fig. 290) may be applied to a servo system as shown in figure 292. Considerable similarity may be noted between this system and the Ward-Leonard system (fig. 282). The primary difference is the use of the amplidyne to replace the d-c generator. The control amplifier is basically the same as that shown in figure 291 except that an additional stage of amplification and an anti-hunt circuit have been added.

(2) To illustrate the action of the control amplifier, assume that the handwheel is turned through some angle. The rotor of the selsyn generator G2 induces in the stator winding a new direction of field which is transmitted to the stator winding of selsyn control transformer CT1. The rotor winding of CT1 which has been in a position of zero induced voltage now develops an error voltage which is fed to the control amplifier input. Depending upon which way the handwheel is rotated, this voltage is either in phase or 180° out of phase with the 120-volt a-c line voltage. For the purpose of describing the control action, an in-phase condition will be assumed as shown by the small sine waves of input voltage in figure 292.

(3) A positive half-cycle of the voltage from the rotor applied to transformer T1 causes point A to be positive while point B is negative. Hence the grid of V1 is positive while the grid of V2 is negative. During the same time a positive half-cycle is applied to transformer T2 causing points C and D to be positive with respect to ground, so that the plates of both V1 and V2 are positive and the tubes conduct according to the grid voltages. Thus, V1 conducts more heavily than V2. The increased IR drop through R6 charges capaci-

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tor C1 with a polarity as shown in figure 292. During this same positive half-cycle, tubes V3 and V4 remain inoperative because the cathodes are positive relative to the plates.

(4) On the following negative half-cycle the grids of V1 and V2 interchange in polarity, but since point D on transformer T2 is now negative, V1 and V2 have a negative voltage on their plates due to the reversed polarity on T2 and conduct if their grid voltages are above cut-off. The biases on the grids of V3 and V4 are produced by the combination of a positive voltage existing between C and D on

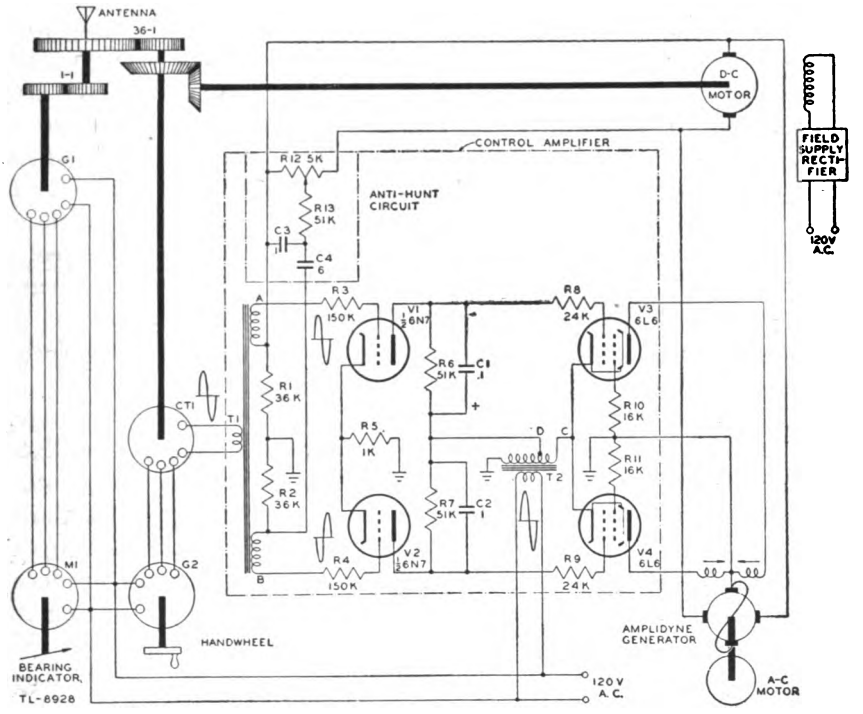

Figure 292. Amplidyne servo system.

the transformer winding in series with negative voltages caused by the charges on C1 and C2. Since C1 has a greater charge than C2, the grid of V3 is more negative than that of V4. The result is that V4 conducts more than V3. Equal currents in the plate circuits of V3 and V4 would produce equal opposing fields in the amplidyne, as shown by the arrows and the resultant field would be zero. However, when V4 conducts more heavily than V3, there is a net field flux and the amplidyne furnishes power to the drive motor. To rotate the drive motor in the opposite direction, V3 must conduct more than V4. This condition is brought about by an input into T1 inverted in phase from the input assumed in the foregoing discussion.

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(5) As soon as the drive motor has rotated the antenna so that the rotor winding of CT1 is again at right angles to the stator field, the input voltage to T1 is again zero and the drive motor stops. To prevent overshooting of this final antenna position, with its consequent hunting effects, a feedback voltage is taken from the amplidyne output terminals and placed across the voltage divider R12. A portion of this voltage is applied to resistors R1 and R2 in series by means of capacitor C4. R13 and C3 comprise a filter network to reduce generator ripple.

(6) If, as an example, the amplidyne voltage begins to build up as a result of an input voltage from the selsyn rotor, C4 starts to charge through R1 and R2. Since R1 is in the grid-cathode circuit of V1 and in series with the split secondary winding of the transformer, any voltage developed across R1 appears as additional grid voltage on V1. The same is true of R2 with respect to V2. The polarity of the feedback voltage is such as to aid the error voltage which is applied to the grids from the secondaries of T1. The extra amplifier unbalance caused by the feedback voltage is small at the start, but the effect is cumulative. The faster the amplidyne voltage increases, the greater the unbalance becomes to cause even further increase in output. In this manner the antenna-drive motor receives extra power to accelerate the antenna turntable.

(7) The charge on C4 reaches a maximum as the amplidyne output voltage levels off to a substantially constant value, and the feedback voltage drops to zero. As the antenna approaches the final position required by the field position of G2, the rotor of CT1 supplies a diminishing voltage to T1. As soon as this occurs capacitor C4 begins to discharge through resistors R1 and R2, and voltages are produced across R1 and R2 which are the reverse of those present during the charging of C4. The feedback now tends to offset rather than to aid the error voltage in the secondaries of T1. The reversed feedback voltage resulting from the discharge of C4 reduces the amplidyne output still further. Since the action is again cumulative, the result is a rapid decrease of amplidyne output.

(8) With feedback potentiometer R12 properly adjusted, the output of the amplidyne falls to zero in time to compensate for the inertia of the driving motor and rotating antenna parts. In such case the antenna stops so that no error voltage is induced in the rotor of CT1 to unbalance the amplifier further. If the amount of feedback, as determined by R12 is too great, the antenna stops too soon, with the rotor of CT1 out of the zero voltage position. The drive motor then starts up rapidly and a condition for high frequency hunting is established. On the other hand, insufficient feedback prevents the anti-hunt circuit from exerting enough effect to overcome inertia, and

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the system hunts at some low frequency. A condition of violent hunting can also arise if the feedback voltage is not of the proper polarity.

d. Aided tracking. (1) In some instances the motion of a target may be such that its rate of change of bearing may be constant. The operator can follow the target by continuous adjustment of the handwheel, but he will be able to concentrate better on the task of observing the screen if the antenna is kept on target by some mechanical means. A system for providing this aided tracking is shown in

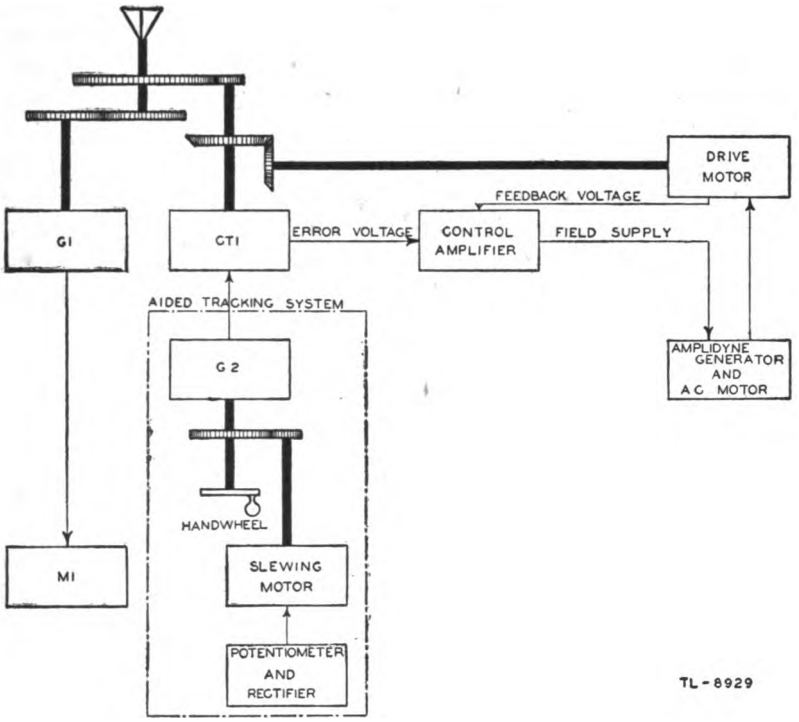

Figure 293. Aided tracking system applied to amplidyne servo system.

figure 293. The rest of the amplidyne servo system is shown only in block form because it is identical with the servo system in figure 291.

(2) The potentiometer controls the speed of a small d-c motor, usually called a slewing motor, which is used to turn the rotor of selsyn generator G2. This rotation produces a rotating field in the stator of the control transformer. The output from the rotor of CT1 causes the servo motor to turn the antenna in such a direction that the error voltage will fall to zero. There must always be a small lag between the axis of the rotor of CT1 and the axis of the stator field in order to produce an error voltage while the rotor of G2 is

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being turned. Since the potentiometer controls the speed of the slewing motor, it also controls the rate at which the antenna turns. Thus, the operator may adjust the potentiometer to the proper rate and then concentrate on the screen of the indicator.

(3) The instances in which the slewing motor is useful to provide aided tracking are somewhat infrequent. However, the same circuit is very useful in providing a means of continual search. For example, the antenna of a system using both PPI- and A-scan indicators might have the aided tracking attachment. In searching for a target, the antenna is rotated at a constant rate under the control of the potentiometer. When it is desired to determine carefully the range and bearing of the target, the slewing motor is disconnected and the antenna rotated by use of the handwheel, and the range is determined from the A-scan indicator.

(4) Aided tracking systems have been developed to a point where the tracking becomes completely automatic, that is, the receiver is gated so that the echo signals from a selected target may be used to control the servo system. Thus the antenna beam locks in on the target and follows it in azimuth and elevation within the limits of the radar set.

e. True and relative bearing. (1) There are certain radar applications where the entire mount supporting the radar equipment may change its position with respect to the target. In such cases it may be desirable to add an automatic compensating feature which keeps the antenna on target. Such devices are needed especially for radar installations aboard ship.

(2) Figure 294① illustrates a ship's course which is 030° true, *degrees true* referring to degrees clockwise from true north. The radar antenna is trained on a target X which bears 35° relative, *degrees relative* referring to degrees clockwise from the bow of the ship, or 065° true. The ship now changes its course an additional 15° to the right (fig. 294②) and proceeds on this new course of 045° true. Therefore, to keep on target the radar antenna on the ship will have to be rotated 15° to the left in order to keep the beam pointed 065° true.

(3) The antenna shift may be performed automatically by replacing selsyn generator G2 (fig. 292) with differential selsyn generator DG1, as shown in figure 295. In G2 (fig. 292) the position of the stator field which establishes the antenna position is determined only by the mechanical position of the single-winding rotor which is turned by the handwheel. In DGI (fig. 295) the direction of the rotor field can be varied by two means: mechanically by means of the handwheel, and electrically by means of the voltages impressed on the three rotor windings.

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(4) Electrical positioning is accomplished by transmitting a true bearing indication from the ship's gyro compass through selsyn generator G3. For example, in the case of the change in the ship's course (fig. 294) the ship's gyro transmits the 15° change in course to the right to the rotor of G3 which produces the 15° change in the rotor field of D1, hence in CT1, and on through the control system. The antenna, therefore, would be shifted automatically 15° to the left (fig. 294②).

(5) If an emergency makes it impossible to operate the radar system with the true bearing connection from the ship's gyro, a pro-

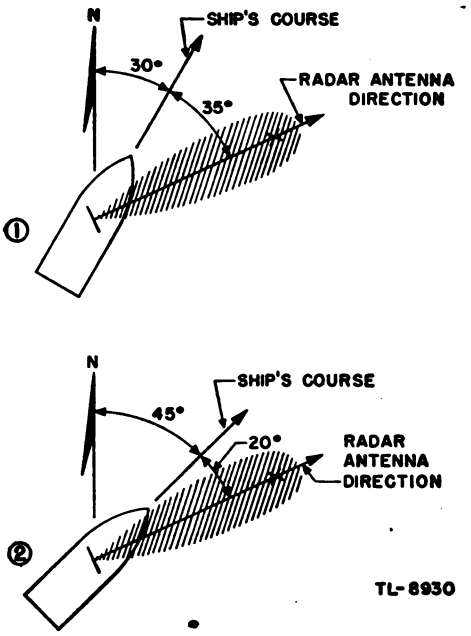

Figure 294. True and relative bearing.

vision is made to supply the three-winding rotor of DG1 from the 120-volt a-c line. DG1 then acts as a simple selsyn generator instead of as a differential selsyn (fig. 295). For true bearing operation, switch S1 is thrown up; for emergency operation S1 is thrown down, and only relative bearing can be shown. An auto-transformer is provided to furnish 78 volts, the correct voltage for the selsyn windings. For the *true bearing* operation the excitation supplied to DG1 comes through G3, but for relative bearing operation the excitation comes directly from the a-c line supply.

(6) It is common with systems employing true bearing correction to provide also another complete selsyn indicator system which transmits a true bearing indication from the ship's gyro compass. The

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information from both indicator systems is then placed on a special bearing indicator dial (fig. 296). The outer dial is fixed. The selsyn at the antenna controls the position of the diamond-shaped pointer, called a bug, and the inner dial is rotated by a selsyn controlled by

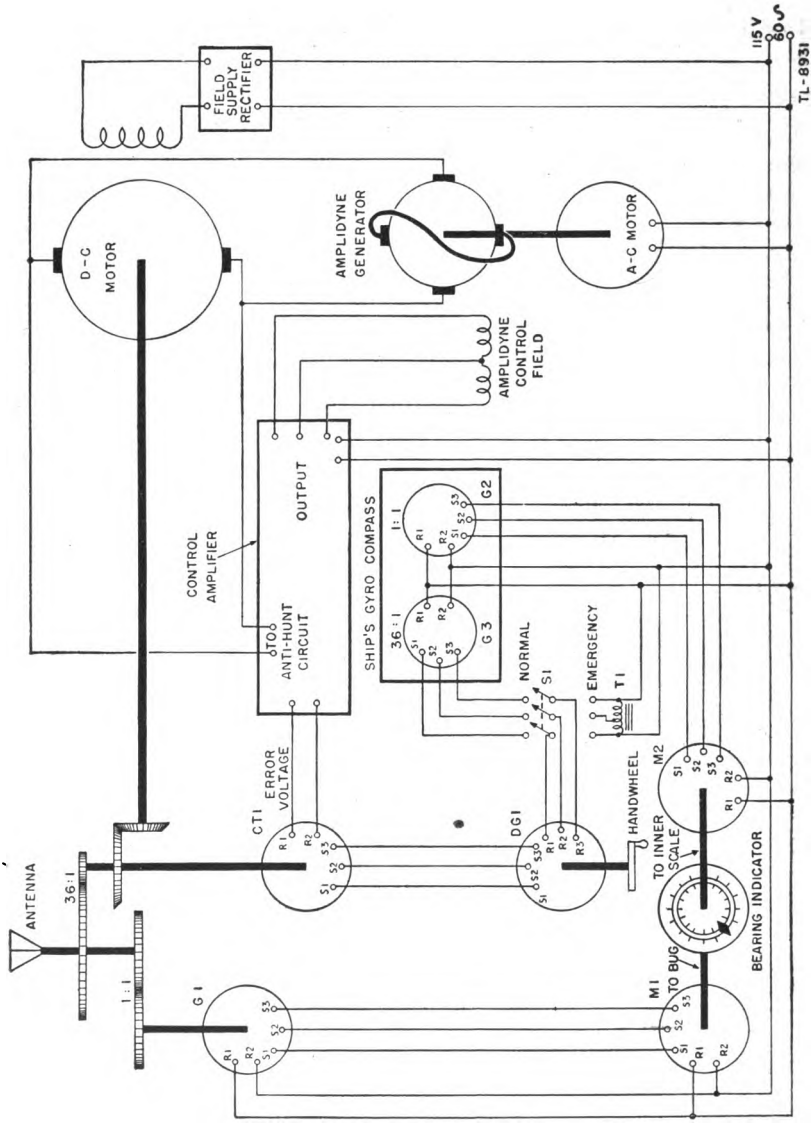

Figure 295. True and relative bearing control.

the ship's gyro compass. Thus the reading on the outer dial opposite the pointer is the true bearing. In figure 295, M1 and G1 form one indicator system transmitting antenna position, and M2 and G2 form the systems giving the gyro compass position.

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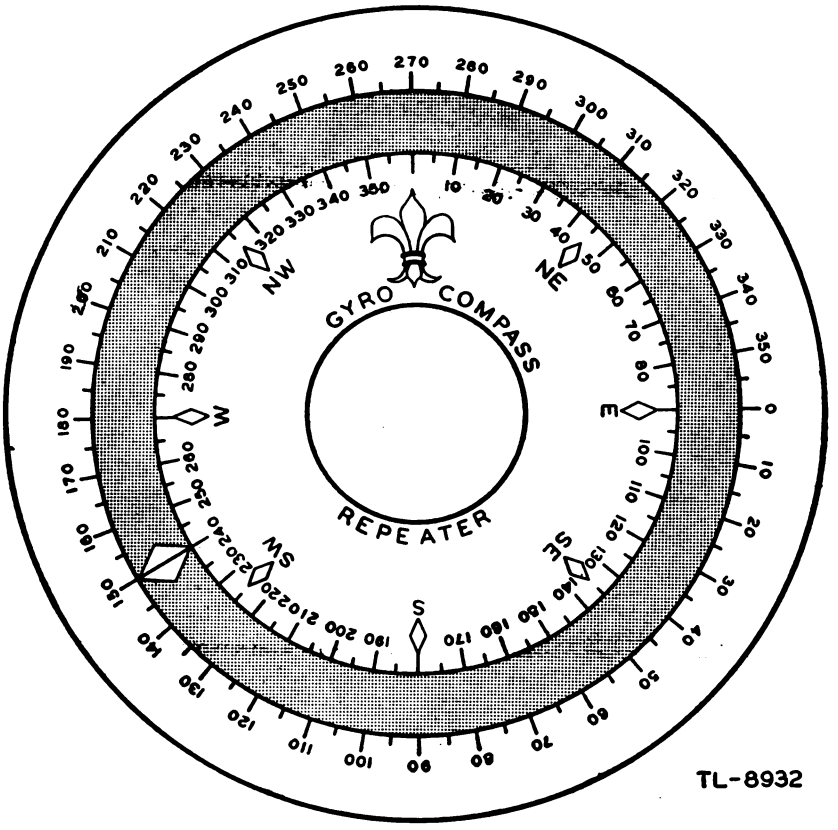

Figure 296. Bearing indicator.

62. TWO-PHASE A-C SERVO SYSTEMS.

a. Two-phase a-c motor. (1) The output drive motor in a servo system should be easily reversible and should have variable speed over a fairly wide range. Ordinarily, an a-c motor cannot fulfill these requirements completely because the range of speed control is limited. However, the use of an a-c motor may provide a much simpler drive system, especially where an a-c power source is available and where some sacrifice in range of speed control can be made.

(2) An a-c motor which can be adapted for servo-system use is the two-phase induction motor. This motor consists of two stator windings spaced 90° electrically from each other and either a wound rotor or a squirrel cage rotor. The latter type of rotor is probably the most common. It consists of heavy conducting bars set into the armature slots and shorted by conducting rings at the ends. The schematic diagram for such a motor is shown in figure 296. The voltages fed to the two stator windings must be 90° out of phase. This 90° phase

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difference plus the effect of the 90° mechanical spacing of the windings results in a rotating magnetic field. The rotating field induces a voltage in the rotor by transformer action, and hence the rotor is turned by the interaction of the magnetic fields present.

(3) Since a two-phase a-c supply is rarely available, it is customary to operate the two-phase motor from a single-phase supply by placing a phase-splitting capacitor in series with one of the stator coils. The current through this coil then leads the voltage by some angle less

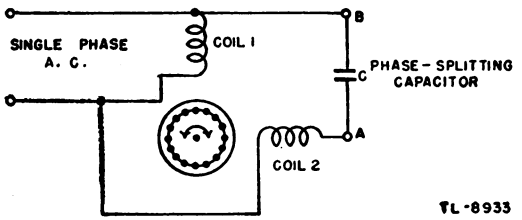

Figure 297. Two-phase motor operating from single phase supply.

than 90°, while the current through the other coil lags by an angle less than 90° because of the reactance of the winding. If a capacitor of the proper size is chosen, the current in the two windings can be made to have nearly 90° phase difference, as required for the rotating field.

(4) Since the capacitors required for induction motor applications are large in size, an equivalent effect may be obtained by the use of a

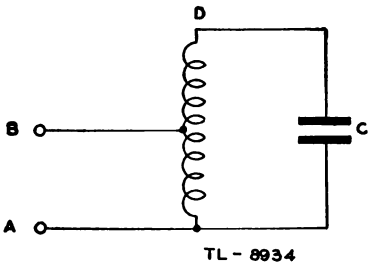

Figure 298. Auto-transformer and capacitor used for phase splitting.

smaller, higher voltage capacitor and a small auto-transformer. Figure 298 shows the circuit frequently used. The auto-transformer can be regarded as an impedance changing devise which reduces the high reactance of a small capacitor between *A* and *D* to the lower reactance of a large capacitor between *A* and *B*. The output terminals of the auto-transformer and capacitor may be connected to points *A* and *B* in figure 297 instead of the capacitor alone.

(5) In order to give wider range of speed control and better torque characteristics for radar antenna-drive applications, it is possible to

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make certain other modifications of the two-phase motor. These include increasing the resistance of the rotor bars and use of the stator coil connections shown in figure 299 to give more starting torque and greater rotor *slip* over the operating speed ranges. This diagram differs from that of figure 297 in that the phase-splitting capacitor is placed in parallel with one coil, and the combination is placed in series with the second coil. The current through coil 1 is made up of the current that passes through coil 2 and capacitor *C* via the autotransformer. Since the current through the capacitor is leading the current through coil 2, the total current through coil 1 leads that through coil 2. The capacitor is chosen to give approximately a 90° phase shift between the current in coils 1 and 2. Thus, the desired rotating magnetic field is produced. A motor so connected tends to give a more constant current input over its speed range, and a much wider range in speed. The efficiency, however, is relatively poor.

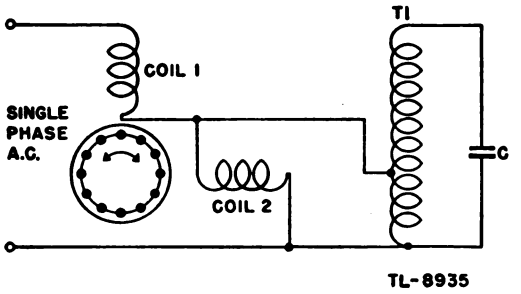

Figure 299. Two-phase motor with series stator coil connections.

(6) The direction of rotation of a two-phase motor is reversed either by reversing the connections to one stator coil or by shifting the capacitor from one coil to the other. The speed of the motor is varied over a limited range by changing the voltage applied to the motor. The voltage may be changed by placing a variable impedance in series with one or both phases. The effect of such an impedance is to lower the voltage, and hence the current, input to the windings without absorbing an excessive amount of power in the control device.

b. Two-phase a-c motor applied to servo system. (1) A servo system which is to be used for radar antenna control should provide an output that is variable in both direction and speed of rotation. However, in applications where it is desired only to turn the antenna to a certain bearing, as in an IFF interrogator, without the necessity of continuous rotation under control of a handwheel, the servo output need not have a wide range of speed variation. Since a two phase a-c motor has a limited range of speed variation, it can be adapted to a servo system which is designed primarily

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for position control. The basic requirements for such a system are: a means of using an error signal to vary an impedance in series with the motor in order to control the speed, and a means of comparing the phase of the error signal with a reference voltage in order to control the direction of rotation of the motor.

(2) The block diagram of a typical servo system in which a two-phase a-c motor is used to provide the output power is shown in figure 300. A selsyn control transformer, CT1, is used to provide an error signal which is proportional to the difference between the actual

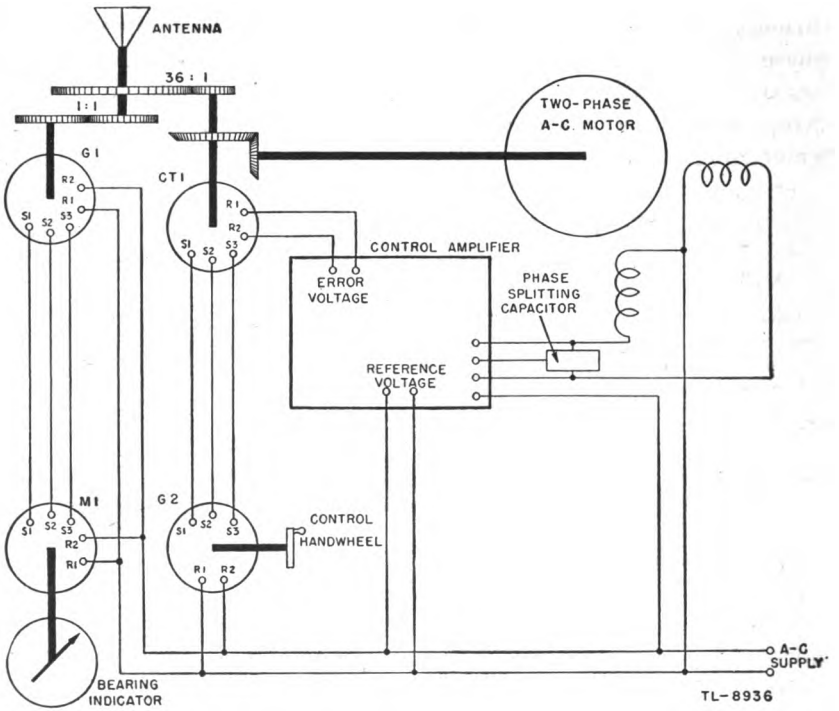

Figure 300. Block diagram of servo system using two-phase a-c motor.

antenna position and the desired position. The rotor of CT1 is geared to the antenna so that rotation of the antenna turns the rotor toward the position in which no error voltage is induced. The antenna is rotated by turning the control handwheel on selsyn generator G2, since this shifts the stator field of the control transformer and thus causes an error voltage to be induced in the rotor. The error voltage is fed to the control amplifier where it is applied in a bias amplifier which varies the impedance in series with the a-c motor to control the speed of rotation. The error voltage is also fed to a direction amplifier where its phase is compared with the phase of a reference voltage in order to control the direction of rotation. The

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load on the direction amplifier circuit is the coil of a relay which selects the stator winding with which the phase-splitting capacitor is connected in series.

(3) The schematic circuit diagram of the control amplifier is shown in figure 301. The error signal is applied to T1 in the bias amplifier. The output of the bias amplifier is a voltage that controls the conduction of tube V5, which is across the primary winding of transformer T3. The turns ratio of T3 is 50 to 1 step down from the primary, so that the impedance transformation ratio is approximately 2,500 to 1. When V5 is conducting heavily, it is effectively a low impedance, so that the impedance in series with the motor is very low, causing it to rotate at full speed. When V5 is cut off, the impedance across the primary of T3 is very high, so that almost all of the line voltage appears across the secondary, preventing the motor from rotating. In other states of conduction, the impedence reflected into the secondary causes the motor to rotate at a speed which is dependent, over a limited range, on the amplitude of the error signal applied to the bias amplifier.

(4) The bias amplifier acts partly as a rectifier and filter network and partly as a d-c amplifier. The input stage is connected as a full-wave rectifier in order that the error signal may be effective, irrespective of its phase. The conduction of V2.1 is controlled by this rectified error voltage, and this conduction determines the voltage to which C1 is charged. The following three stages of the bias amplifier are similar to the first, so that the charge on the capacitor in each stage is dependent on the voltage to which the preceding capacitor was charged. For example, when the error signal is zero, V2.1 is almost cut off by the self bias developed across C2 and R4. In this condition, most of the plate voltage appears across V2.1 and the voltage across C1 is very small. The following stage is nearly at zero bias, then, so that C3 is charged to a high voltage which cuts off V3.1. By a similar analysis, it may be found that the voltage across C5 is maximum when the error signal is zero, so that V5 is cut off in this condition, preventing the motor from rotating.

(5) In the direction amplifier the phase of the error signal that is applied to T5 is compared with the phase of the reference voltage which appears across T6. If these voltages are in phase, V3.2 conducts heavily on alternate half cycles, causing C8 to be charged to a large voltage. The voltage across C8 prevents conduction of V4.2 so that C10 is able to discharge. Thus, V6 is operated at zero bias and the relay is operated by the plate current of V6. The relay connects the phase-splitting capacitor in series with stator winding S1, causing the motor to rotate clockwise. If the error signal is 180° out of phase with the reference voltage, V6 is cut off by the voltage that appears

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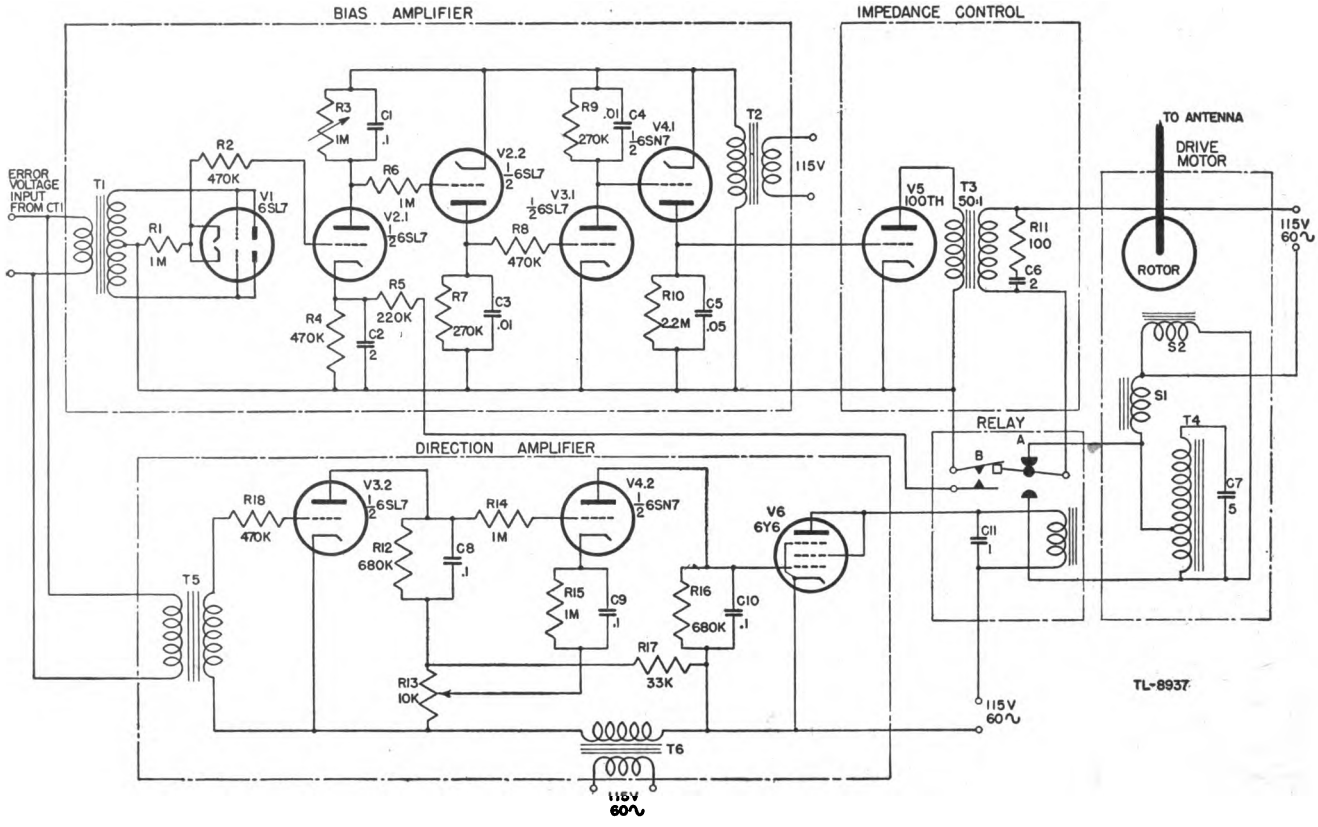

Figure 301. Schematic circuit diagram of control amplifier.

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across C10, and the relay closing coil is not energized. In this condition, the relay connects the phase-splitting capacitor in series with stator winding S2, causing the motor to rotate counterclockwise.

(6) It is desirable that the antenna approach the desired position slowly so that it may come to rest without excessive hunting. This is accomplished by the use of C2 and R4 in the cathode of V2.1. Capacitor C2 charges through V2.1 while the error signal allows the tube to conduct, but the capacitor must discharge through R4 when V2.1 is cut off. As the antenna approaches the desired position, the amplitude of the error voltage decreases so that the output of the bias amplifier causes the motor to slow down. At some time before the desired position is reached V2.1 is cut off because of the increased voltage across C2. Thus, the antenna must coast toward its ultimate position.

(7) The R-C circuit in the cathode of V4.2 has a similar effect on the direction amplifier. As the error voltage decreases, the charge on C10 either builds up or decays, depending on the direction of rotation. At the time when the antenna passes through the desired position the relay snaps to its other position, causing the motor to reverse to counteract the inertia of the moving antenna. In switching from one position to the other, the *B* contacts on the relay are momentarily closed. This action reduces the time constant of the discharge of C2 by shunting R5 across R4, so that the bias on V2.1 is reduced to approximately its normal magnitude. The overtravel of the antenna causes an error voltage to be produced which energizes the motor to bring the antenna back to the desired position.

(8) The system is purposely designed to operate with small overtravel because the critical damping condition is too hard to maintain. The amount of overshooting that takes place is adjusted to a satisfactory minimum by the setting of the bias amplifier sensitivity control R3 and the direction amplifier sensitivity control, R13.

63. HYDRAULIC DRIVE.

a. General. (1) Hydraulic methods of position control were in use before the electrical servo systems were developed. Because hydraulic systems are capable of controlling large amounts of power, they are widely used to turn the rudders of ships and to control other heavy mechanisms. The hydraulic system has the advantage of low inertia in its moving parts which enables a very fast response to be obtained. However, it has the disadvantage that the fluid system is difficult to keep in good working order. The high pressures involved tend to cause leaks at rotating joints, and extreme temperatures affect the ease with which the hydraulic fluid can flow.

(2) The hydraulic drive consists essentially of a high-pressure variable-flow pump using some fluid such as oil and a hydraulic motor

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connected to the pump by pipes. A typical variable-flow pump is shown in figure 302. It consists of a rotating cylindrical block containing several pistons uniformly spaced in a circle around the center of the block.

(3) The axes of the small cylinders into which these pistons fit are parallel to the axis of the cylinder block. The whole assembly is mounted in a tilt box or cylinder head in which the cylinder block rotates. As the block turns, the small cylinder openings pass under inlet and outlet ports in a valve plate. The cylinder block is driven by a drive plate through a universal joint so that the axis of the block

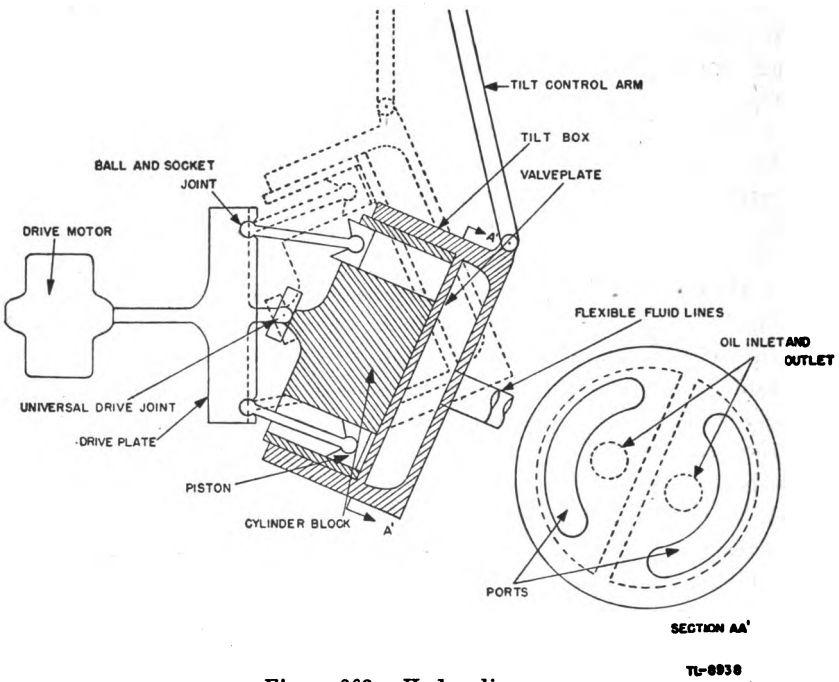

Figure 302. Hydraulic pump.

may be changed by an angle of as much as 30° either side of the main drive shaft center line. This angle causes the small pistons, attached to the drive plate by ball-and-socket joints, to move in and out of the block as it rotates. The greater the angle of the block, the longer the piston stroke; the smaller the angle, the shorter the stroke. At zero angle there is no relative motion between the piston and the cylinder block and therefore no pumping action. As the angle of the block passes through zero to the opposite side of the drive-shaft center line, the position of the pistons changes with respect to the inlet and outlet ports. The piston which was on compression stroke is now on suction stroke. This position change results in a reversal of direction of the pumping action.

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(4) The pump is operated at a constant speed with the pumping action dependent on the angle of tilt. Thus a change of the angle by means of a mechanical linkage serves to control both the amount and direction of flow.

(5) The hydraulic motor is similar in construction to the pump, but the cylinder block has a fixed angle of tilt of approximately 30°

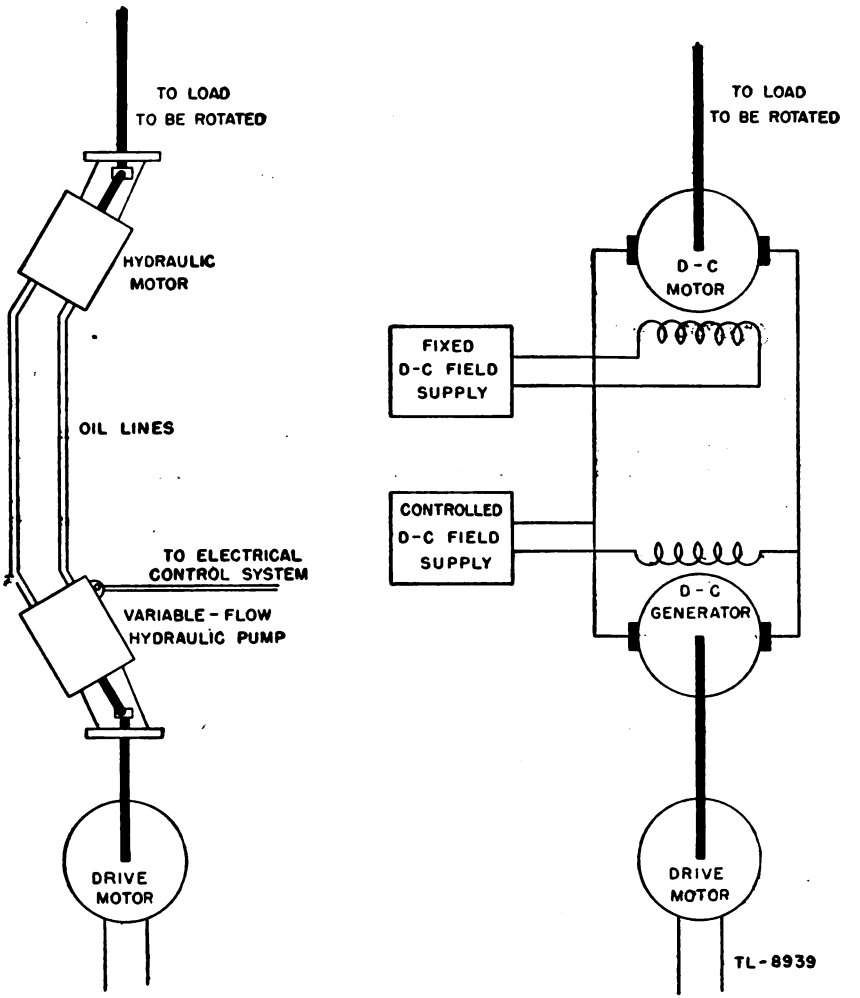

Figure 303. Comparison of hydraulic drive and Ward-Leonard drive.

with respect to the drive shaft. Other types of pumps and motors are in use, but their principles of operation are in general similar to those just discussed.

b. Application of hydraulic drive. (1) A comparison of the hydraulic drive and a simple Ward-Leonard drive is shown in figure 303. The controlled d-c field supply for the Ward-Leonard

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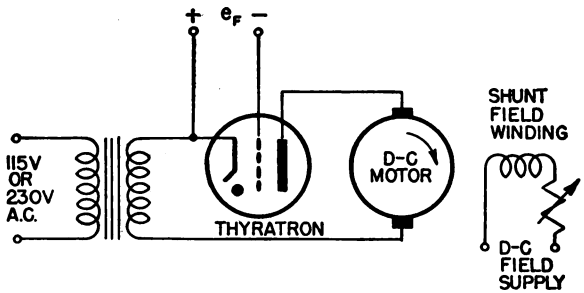
generator is replaced in the hydraulic drive by a mechanism which varies the pump angle. Such a mechanism can be operated electronically from a selsyn error voltage as in the Ward-Leonard or amplidyne servo system.

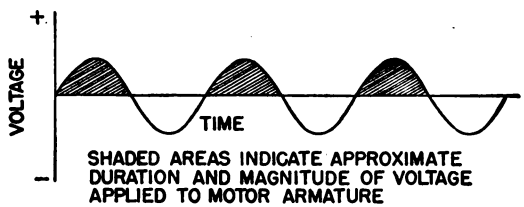
(2) At present, hydraulic drives find limited application in radar work and are confined chiefly to stabilization controls for main battery fire-control antennas aboard ship. They are used frequently, however, in controls for large guns and other ordnance equipment.

64. THYRATRON MOTOR CONTROL.

a. Basic thyratron motor drive. (1) A type of d-c motor control which is used in some radar applications employs thyratron tubes. The basic circuit for this system is shown in figure 304①. If



① THYRATRON MOTOR CONTROL CIRCUIT



② PLATE VOLTAGE AT THYRATRON

TL-8940

Figure 304. Basic thyratron motor control circuit.

the grid of the thyratron V1 is biased above the critical grid-voltage value which corresponds to cut-off in an ordinary tube, the tube acts as a half-way rectifier. Therefore pulsating direct current is supplied to the armature of the d-c motor approximately in accordance with the voltage curve (fig. 304②). However, if the grid bias is made sufficiently negative, the thyratron will be blocked and the motor armature will receive no current.

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(2) In the circuits as shown, the thyratron thus performs two functions. It acts as the rectifier for the direct-current supply to the armature, and it acts as a switch to turn the supply on and off according to whether the thyratron grid is biased above or below the critical value, which controls the firing of the tube (sec. IV, TM 11–466 and Navships 900,016). The transformer (fig 304①) may be omitted in certain instances, although if standard-voltage d-c motors are used, a transformer is usually necessary.

(3) Providing the grid voltage is properly modified, the third function which the thyratron can accomplish is that of speed control. The motor speed can be controlled by varying the rheostat in the separately excited field circuit if the armature is supplied at a reasonably constant voltage. It is more common, however, to control the armature current and either excite the fields separately at some constant value or provide series fields through which the controlled armature current may flow.

(4) The grid of the thyratron does not directly control the magnitude of the current flow through the tube, but merely the firing point or the value of plate-to-cathode voltage at which tube current starts to flow. Therefore, the bias on the grid can only cause the tube to act as an off-on switch. However, it is possible to superimpose an a-c voltage on the grid bias and cause the tube to conduct during various portions of its conducting half-cycle.

(5) Figure 305① shows a bias voltage e_F which is more negative than the critical voltage, e_C; therefore, no appreciable current can flow through the tube. The horizontal line at e_E, in figure 305① represents the minimum plate-to-cathode voltage that can maintain ionization in a thyratron, irrespective of the grid potential. This voltage is called the extinguishing voltage. In figure 305② e_F has been made less negative, and the tube conducts over a major portion of the cycle. Conduction does not begin until the grid voltage is more positive than the critical value and the plate-to-cathode voltage is sufficient to maintain ionization of the gas in the tube. Conduction stops after the voltage has dropped below the deionizing point. Therefore, the shaded area (fig. 305②) does not occupy quite the entire half-cycle. The curve of the critical grid voltage, e_C, is not a straight line because this voltage varies according to varying plate-to-cathode potentials. For example, at the peak of the applied voltage wave, e_C must be considerably more negative than at the half-voltage point on the wave, and at very low plate-to-cathode potentials the grid must be positive to cause the tube to fire.

(6) Figure 306① shows the result of applying an a-c grid voltage, e_G, superimposed on the bias voltage e_F. At time X, the instantaneous grid voltage reaches the critical value shown by curve e_C and causes

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the thyratron to conduct. Since the grid then loses control, the tube conducts to time Y when the plate-to-cathode voltage becomes so low that ionization cannot be maintained. The a-c grid voltage (fig. 306①) is of the same frequency as and in phase with the a-c supply to

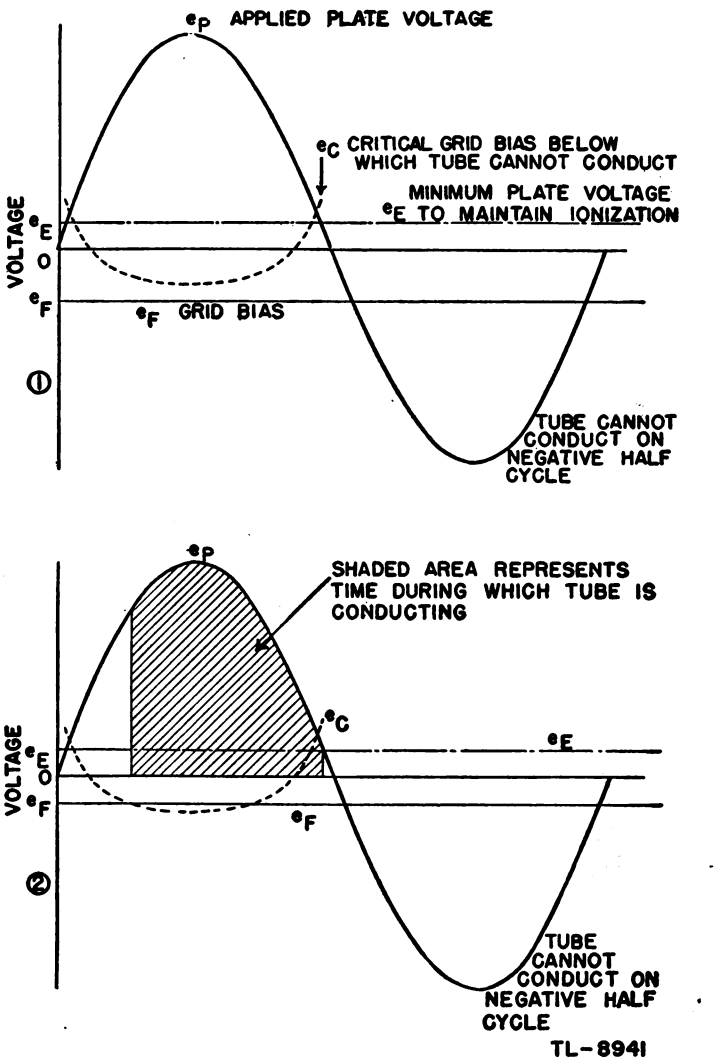

Figure 305. Control of conduction of thyratron by grid bias.

the tube plate. If the bias is kept the same, as well as the frequency and magnitude of e_G, but the phase is caused to lag the plate supply by 45°, the condition shown in figure 306② results. The time at which the curve of e_G intersects that of e_G, is later than in figure 306① and therefore the tube conducts during less of the half-cycle. In figure

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306③ the lag is 90° so that the point of intersection of curves e_G and e_G is still farther to the right, and the tube conducts over a still smaller portion of the cycle. In fact, at a lagging phase angle of, for example, 140° (fig. 306④) the grid voltage is never sufficiently positive at the right time to cause the tube to conduct at all. The same effect can be

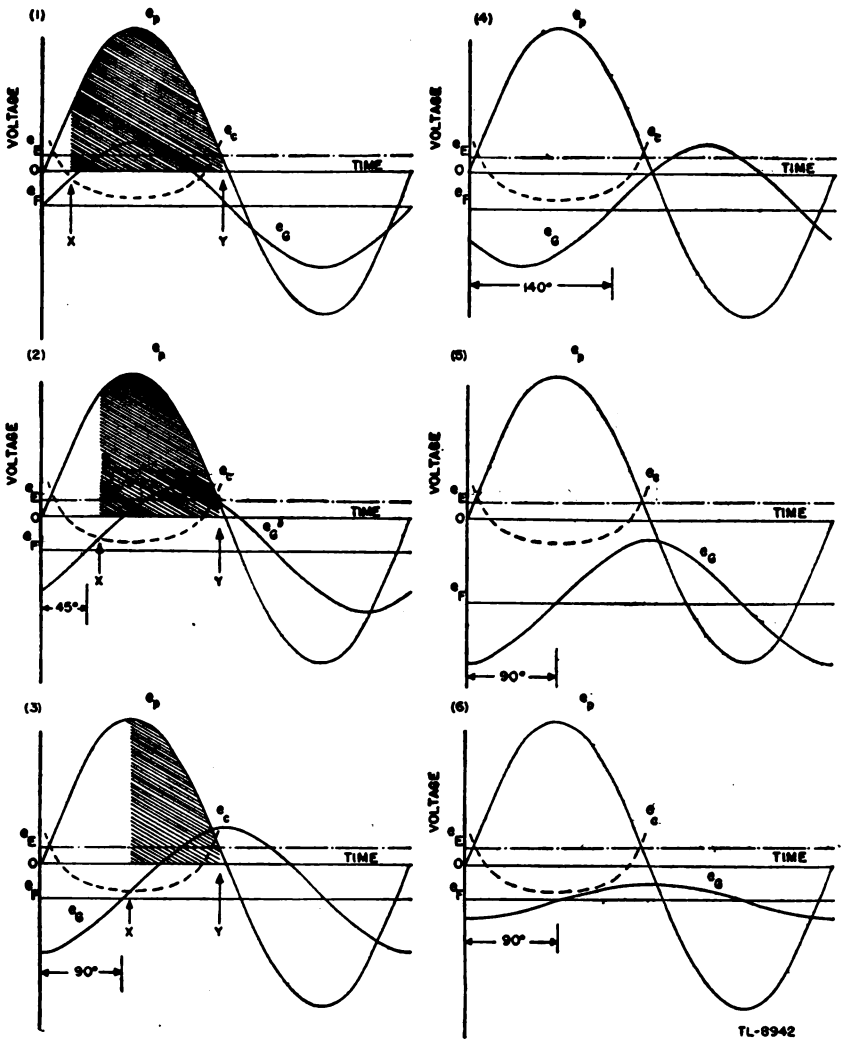

Figure 306. Control of firing point of thyratron by sine wave on grid.

achieved by making the bias more negative (fig. 306⑤) or by reducing the amplitude of the a-c component of grid voltage (fig. 306⑥).

(7) It can be seen from the foregoing discussion that by causing the thyratron to fire at various points in its conducting half-cycle, the tube can be used not only as a switch and a rectifier, but also as a

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device to control the average amount of current flowing. Thus, the thyratron (fig. 304①) can control the starting, stopping, and speed of the d-c motor by controlling the flow of the current to the armature.

(8) Figure 307 illustrates the way in which the thyratron may be fired by means of a trigger pulse. In order to control the thyratron output, it is necessary to have a phase-shifting device to vary the

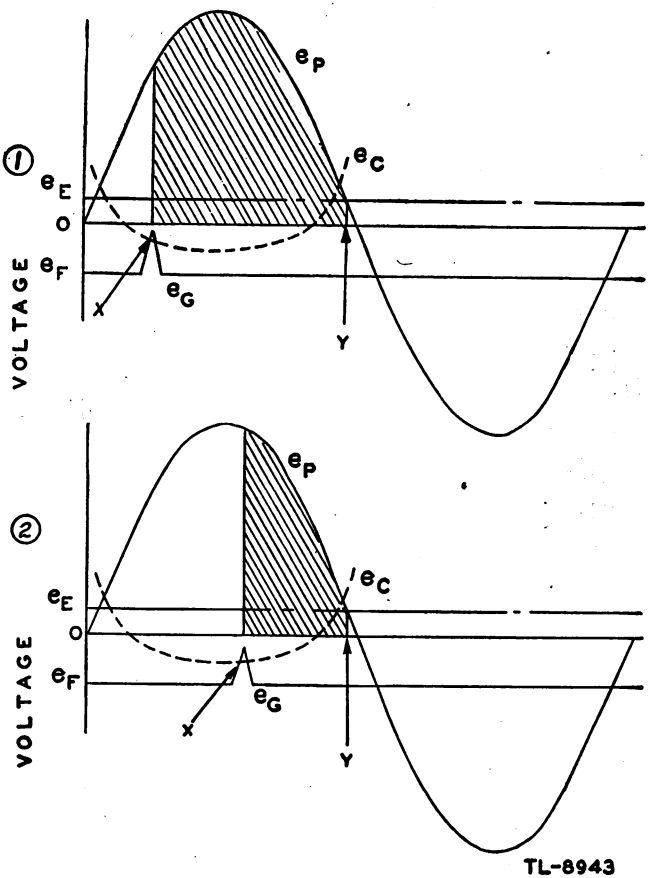

Figure 307. Control of firing point of thyratron by pulse on grid.

position of the pulse with reference to e_P. The bias and pulse amplitude are adjusted so that the pulse rises above the e_C curve as before.

(9) Up to this point no mention has been made of how the direction of rotation of the motor of figure 304① is to be changed. Since a single thyratron can function only as a half-wave rectifier, no modification made on the grid voltage can change the polarity of the output. In order to reverse the motor, then, it is necessary either to reverse the polarity of the field supply or to reverse the polarity of the armature supply.

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(10) Figure 308 shows a motor-control circuit using two thyratrons. V1 provides current for one direction of armature rotation, and V2 provides current for the opposite direction. It is quite important in this type of circuit that only one of the tubes be permitted to conduct at a time. If both grids are sufficiently positive to fire the tubes on both halves of the cycle, the armature is subjected to an alternating current, and serious damage to the motor and thyratrons may occur. The field supply remains fixed in polarity and magnitude in this circuit.

(11) Any circuit, such as shown in figure 308, using a separately excited field and supplying a fairly large d-c motor, should have a relay interlock arrangement. Thus, if the field supply becomes open-

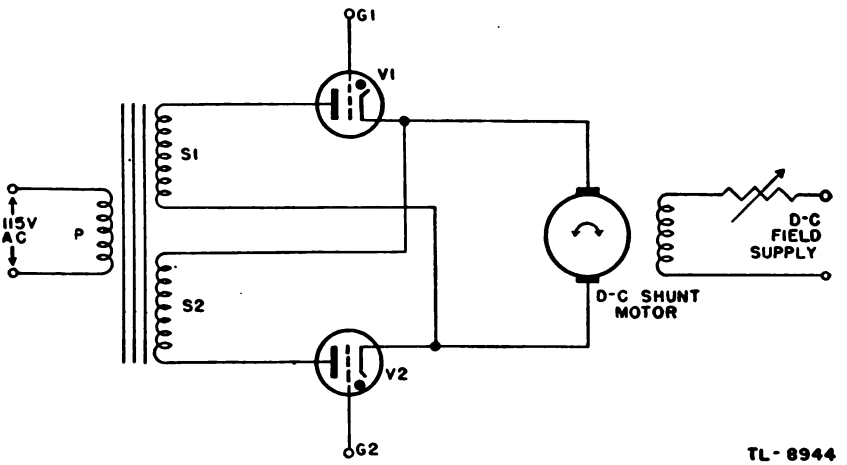

Figure 308. Reversible thyratron-controlled motor.

circuited, the armature circuit is also opened. The interlock is necessary because the speed of a shunt motor increases enormously, and the armature draws excessive current when the field flux falls to zero since the counter-emf which limits the armature current becomes zero, and the armature resistance is usually too low to prevent a damaging surge of current.

b. Application of thyratron motor drive. (1) The reversible thyratron controlled motor (fig. 308) can be applied in a remote-control radar antenna system with the addition of the proper grid control circuits. An example of such a drive is shown in figure 309. The control section is shown in block-diagram form for simplicity.

(2) The grids of thyratrons V1 and V2 are supplied an alternating voltage which is superimposed on a d-c bias. The bias voltage is adjusted to a value that will produce the required speed of rotation when the maximum signal is applied. The magnitude and phase of

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the a-c voltage at each grid is adjusted so that neither tube conducts in the absence of a signal.

(3) The motor is made to rotate by the signal generated in the magneto. If the magneto is turned clockwise, a d-c voltage is generated which reduces the bias on V1, and therefore causes V1 to conduct; if the magneto is turned counterclockwise, the output is of opposite polarity, causing V2 to conduct. Since the average current supplied to the armature of the motor is dependent on the fraction of the cycle during which the thyratron conducts, a greater output from the magneto causes a larger current to be supplied to the motor because the time of firing is advanced by this higher voltage. Thus, the faster the magneto is turned, the faster the antenna turns.

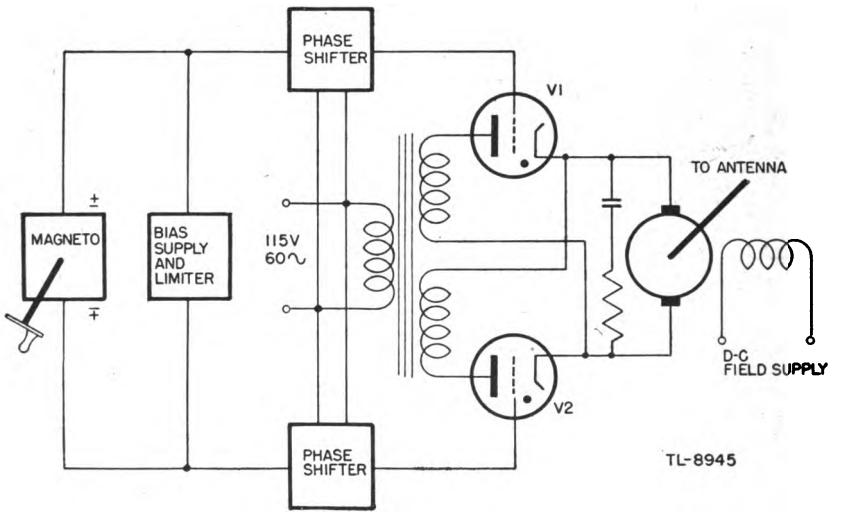

Figure 309. Thyratron motor control system.

(4) Since the current-carrying capacity of the thyratrons is limited, too great a change of bias caused by the signal from the magneto may cause damage to these tubes. Therefore, a limiter is incorporated in the bias supply system to prevent the bias on the thyratrons from becoming less than that which causes the antenna to rotate at five revolutions per minute. As a result, the antenna cannot rotate faster than five revolutions per minute even though the magneto may produce a very large output voltage.

(5) The antenna rotates only as long as the handwheel on the magneto is turned. When the magneto is stopped, the grids of both thyratrons are returned to their normal bias, and no conduction takes place, causing the motor to stop. The resistor and capacitor connected across the motor are used to absorb the transient produced when the motor is stopped suddenly.

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APPENDIX

Glossary of Radar Terms

A-. U. S. Navy prefix to designate airborne equipment. Examples: ASB, airborne search radar; ABK, airborne identification equipment; AYD, airborne altimeter equipment.

AFC. Automatic frequency control. (*See* Frequency control.)

AGL. Aircraft gun laying; radar for plane-to-plane fire control.

AI. Aircraft interception. Radar which enables a night fighter to detect and close with an enemy aircraft.

Aided tracking. A system of tracking a signal in azimuth, elevation, or range, or all three variables together, in which a constant *rate* of motion of the tracking mechanism is maintained by mechanical means such that an equivalent constant rate of motion of the target can be followed. The operator adjusts the rate by controlling an error voltage.

Alignment. (1) The process of adjusting the tuned circuits of a tuned radio-frequency receiver to a predesignated natural frequency.

(2) The process of adjusting two or more components of a system so that their functions are properly synchronized; for example, antenna orientation, and PPI sweep.

Amplidyne. A special type of d-c generator used as a power amplifier in which the response of the output voltage to changes in field excitation is very rapid. Used extensively as part of a servo system.

Amplidyne generator. *See* Amplidyne.

Angular rate. *See* Rate of change of bearing.

Antenna assembly. The complete equipment associated with projecting radar energy into space and receiving it, consisting in general of a mounting base, gears and motors for rotating the radiator, selsyns, potentiometers, the antenna proper, and reflector, together with associated switches.

Antenna matching device. A device which matches the antenna to its transmission line by introducing an impedance which, together with the impedance of the antenna, equals the characteristic impedance of the line.

Antenna reflector. That portion of a directional array, frequently indirectly excited, which reduces the field intensity behind the array and increases it in the forward direction.

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Antenna switching unit. *See* T-R switch.

Antihunt circuit. A circuit in which a portion of the output voltage of a servo system, which is used to drive a rotating antenna system, is fed back into the output circuit in such a phase and magnitude as to prevent the antenna from oscillating about any position.

Anti-T-R Box. *See* Anti-T-R switch.

Anti-T-R switch. A spark gap and transmission line combination which prevents radar echoes from feeding into the transmitter of a radar system.

ARO. Lightweight radar range finder.

Artificial delay line. *See* Delay line.

Artificial transmission line. *See* Pulse-forming line.

A-scan. An indicator with a horizontal or vertical sweep, giving range only. Signals appear as vertical or horizontal deflections on the time scale.

A-scope. *See* A-scan.

ASV. Aircraft to surface vessel. Radar to detect surface vessels from patrol aircraft.

Attenuation (wave). The decrease in amplitude with distance in the direction of wave propagation.

Attenuator. A device for controlling the amplitude of a signal.

Automatic tracking. Tracking in which the servo mechanism follows the signal automatically, and keeps the radar beam oriented on the target.

Autosyn. A trade name. (*See* Selsyn.)

AVC. Automatic volume control. Automatic voltage control.

Azimuth. *See* True bearing.

Azimuth rate. *See* Rate of change of true bearing.

Azimuth-stabilized PPI. The presentation of the radar signals on a PPI tube so that north (magnetic or true) is always at the top of the tube.

B-. U. S. Navy prefix to designate identification equipment. Examples: ABK, BK.

Back swing. A portion of a pulse in which the voltage shifts in the direction opposite to that of the main body of the pulse, and occurs at the end of the main body of the pulse. Compare Tail and Overshoot.

Bandwidth. The number of cycles per second expressing the difference between limiting frequencies at which the desired fraction of the maximum output is obtained (usually determined by the half-power point in the frequency spectrum). Term applied to receivers or transmitters.

Base line (*CRT*). The horizontal (or vertical) line formed by the movement of the sweep on the A-scope.

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Bazooka. A terminating device used to convert an unbalanced line to a balanced condition.

Beacon. An automatic transmitter operated by a radar signal which enables an aircraft to determine its azimuth and range, with respect to the beacon.

Beaded support. Ceramic and plastic beads used to support the inner conductor in coaxial transmission lines.

Beam width. The width (the angle between half-power intensities) in an azimuth of the effective radiation from an antenna. Used in describing directional radiation.

Bearing. The direction of the line-of-sight from observer (radar antenna) to the target. Bearings may be measured relative to own fore and aft axis (own keel line), relative to true north, or relative to compass north. All bearings, unless otherwise stated, are measured clockwise at the position of the observer, from 0° to 360°.

Bedsprings. See Billboard type antenna.

Billboard type antenna. A broadside array with flat reflector.

Blanking voltage. See Indicator gating.

Blip. See Pip.

Blocking oscillator driver. A circuit which develops a square pulse used to drive the modulator tubes, and usually contains a line-controlled blocking oscillator, that shapes the pulse into the square wave.

Bolometer. A type of device used in radio-frequency measurements, for determining standing-wave ratio. The sensitive element absorbs r-f power, its temperature changes, and consequently its resistance is altered.

Bootstrap driver. A special type of vacuum-tube circuit used to produce a square pulse which drives the modulator tube. The duration of the square pulse is determined by the pulse-forming line. The circuit is called a bootstrap driver because voltages on both sides of the pulse-forming line are raised simultaneously with voltages in the output pulse, but their relative difference (on both sides of the pulse-forming line) is not affected by the considerable voltage rise in the output pulse.

B-scan. Type of presentation in which signal appears as a bright spot with azimuth angle as the horizontal coordinate and range as the vertical coordinate.

B-scope. See B-scan.

Calibration marker. See Range marker.

Cat whisker. A wire which touches the crystal in a crystal detector. (*See* Whisker.)

Cavity resonator. A hollow metallic cavity in which electromagnetic oscillations can exist when properly excited. These determine the

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oscillating frequencies of klystrons, McNally tubes, and Sheppard tubes. Frequency is determined by the physical dimensions of the resonator.

Centering diode. A clamping circuit used in some types of PPI indicators. (*See* Clamping circuit.)

Centimeter waves. *See* Microwaves.

Choke-flange joint. A form of wobbly or nonrigid connection between two waveguides, containing an L-shaped cavity.

Choke joints. Metal fittings constructed to give low-transmission losses when joining sections of waveguides.

CIC. Combat information center. U. S. Navy designation for the compartment aboard ship in which all radar information is screened and disseminated. Corresponds to U. S. Army filter center.

Circular scanning. The axis of the r-f beam rotates through 360° in a single plane.

Clamping circuit. A circuit which clamps either amplitude extreme of a wave form to a given reference level of potential.

Clamping tube. *See* Clamping circuit.

Clipper circuit. *See* Limiter.

Coaxial dry load. *See* Sand load.

Color trace crt. *See* Dark trace tube.

Commutator circuit. *See* Direction rectifier.

Compass bearing. Bearing measured relative to magnetic north. (*See* Bearing.)

Compass bearing rate. *See* Rate of change of compass bearing.

Compass error. The angle formed by the north-south compass line and the true meridian passing through the center of the compass.

Conical scanning. A type of scanning in which the tilt angle is fixed so that the axis of the r-f beam generates a cone with a vertex angle usually from 5° to 10°.

Continuity test. An electrical test to determine the presence of a broken connection.

Control central. *See* Timer.

Control transformer. A selsyn in which the electrical output of the rotor is dependent upon both the shaft position and the electrical input to the stator. (*See* Selsyn.)

Cosecant-squared beam. A radar beam pattern designed to give approximately uniform signal intensity for echoes received from distant and nearby objects. Such a beam is generated by a spun barrel reflector. The beam intensity varies as the square of the cosecant of the elevation angle.

Counter circuit. A circuit which receives uniform pulses representing units to be counted and produces a voltage in proportion to their frequency.

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Crystal burn-out. The impairment of a crystal by exposure to excessive r-f power.

Crystal detector. A system composed of a metal wire and a crystal, which offers a higher resistance to current in one direction than to current in the other direction. Conduction depends upon traces of impurities.

Crystal mixer. A housing containing the crystal, inputs for signal and local oscillators, and i-f output. Used in heterodyne detection for converting the received radar signal to a lower frequency for amplification.

Crystal-video receiver. A broad tuning receiver consisting of a crystal detector, followed by a high grain video amplifier.

C-scan. Type of presentation in which the signal appears as a bright spot with azimuth angle as the horizontal coordinate and elevation angle as the vertical coordinate.

C-scope. See C-scan.

Cutler feed. A resonant cavity at the end of a waveguide, which feeds r-f energy to the reflector of the spinner assembly.

Cut-off wavelength. The longest space wavelength which can be conducted down any given waveguide.

Cut paraboloid. See Truncated paraboloid.

Dark trace tube. A CRT with a screen composed of a halide of sodium or potassium, the traces of which may be enlarged by projection. (*See also* Skitron.)

Decibel (*db*). The unit used to express power ratio: db$=10 \log P_1/P_2$, where P_1 and P_2 are the two powers being compared; for example, 3 db down means a 50 percent loss of power.

D–C restorer. See Clamping circuit.

Deflection yoke. Yoke used in magnetic cathode-ray tubes. It has coils wound on it, and controls the electron-beam deflection.

Delay circuit. A circuit which introduces a time delay in the passage of current from one part of the circuit to another.

Delay line. Usually an artificial transmission line used to introduce a short time delay in the transfer of a signal from one circuit to another.

Delayed sweep. See Sweep.

Differential selsyn. A selsyn in which both rotor and stator have similar windings that are spread 120° apart. The position of the rotor corresponds to the algebraic sum of the fields produced by the stator and rotor.

Differentiator circuit. A circuit which produces an output voltage substantially in proportion to the rate of change of the input voltage of current. Differentiating circuits employ short time constants compared to the time duration of the pulse applied.

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Diode clipper. *See* Limiter.

Diode mixer. A mixer in the form of a tube containing cathode and anode, which fits into the r-f line in much the same way as a crystal mixer and performs the same function.

Diplexer. A coupling system which allows a radar and a communication transmitter to operate simultaneously or separately from the same antenna. Not to be confused with the duplexer.

Dipole antenna. Two metallic elements, each approximately one-fourth wavelength long, which radiate the r-f energy fed to them by the transmission line.

Direction rectifier. A rectifier which supplies a d-c voltage varying in magnitude and polarity with the magnitude and relative polarity of an a-c selsyn error voltage.

Discriminator. (1) Radar: A circuit that produces a response which depends upon the frequency of the input signal.

(2) Beacon: A circuit which accepts pulses of proper duration and rejects others.

Dish. *See* Paraboloid.

Display. A CRT screen and dials which present the information obtainable by the radar set; for example, range, azimuth, elevation.

Double moding. Frequency jumping; changing abruptly from one frequency to another, at irregular intervals.

Double-stub tuner. Two stubs, usually fixed three-eighth wavelength apart, in parallel with the main transmission line. Used in matching an impedance to a transmission line, such impedance being, for example, the antenna or transmitting tube.

Drift. *See* Warm-up drift.

Driver. The circuit in the transmitter which produces a pulse to be delivered to the control grid of the modulator stage.

D-scan. Presentation combining B and C types. The signal appears as a bright spot with azimuth angle as the horizontal coordinate and elevation angle as the vertical coordinate. Each horizontal trace is expanded slighty vertically by a compressed time sweep to facilitate separation of signal from noise and give a rough range indication.

D-scope. *See* D-scan.

Duplex cavity. *See* T-R switch.

Duplexing assembly. Combination of T-R switch, and sometimes an anti-T-R switch, with transmission lines.

Duty cycle. The ratio of the pulse width to the pulse repetition time.

Echo. The portion of the energy of the transmitted pulse which is reflected back to the source by a target.

Echo box. A high Q resonant cavity which receives r-f energy through a pickup antenna during the transmitted pulse and reradiates this

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energy through the same antenna immediately after the pulse. The reradiated energy is picked up by the radar set. Since this energy from the echo box dies off exponentially, it will appear on an A-scope indicator as a flat-topped pulse, resulting from the saturation of the receiver by the high energy return, followed by an exponential curve.

Electronic coupling. The method of coupling electrical energy from one circuit to another through the stream of electrons in a tube.

Elevation. Angle of the target, above or below the radar set.

Error voltage. A voltage, usually obtained from a selsyn, the magnitude of which is proportional to the difference between an actual position and a desired position. This voltage controls a servo system so that the resultant motion tends to reduce the error in position.

E-scan. A modification of B-scan. Signal appears as a bright spot with range as the horizontal coordinate and elevation as the vertical coordinate.

E-scope. See E-scan.

Expanded scope. A magnified portion of a given type of CRT presentation; for example, P^3I.

Expanded sweep. A sweep in which the movement of the electron beam across the screen is speeded up during a selected portion of the sweep time.

F-. U. S. Navy prefix to designate shipborne fire-control radar. Examples: FC, FD, FH, etc. Designation later changed to Mark III, Mark IV, Mark VIII, etc.

Filter center. U. S. Army designation for information center at which all radar and other observed information concerning the movement of friendly and enemy planes within a certain sector is screened and disseminated. Corresponds to U. S. Navy CIC.

Firing (as applied to magnetron and T-R switch). The excitation of the device during a brief pulse.

Free-running multivibrator. A multivibrator oscillating at the frequency determined by its own circuit constants.

Frequency control. The regulation of the frequency of a generating system within a narrow range.

Freya. German early-warning radar set.

F-scan. A single signal only, appearing as a bright spot. Azimuth error angle (relative bearing) appears as the horizontal coordinate, elevation angle as the vertical coordinate.

F-scope. See F-scan.

Gate. A square-voltage wave which switches a circuit on or off electronically, usually by application to a grid or cathode.

GCA. Ground control of the approach of an aircraft to an airfield.

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GCI. Ground control of interception. The technique that is accomplished by coordination between a land-based radar set and fighter aircraft equipped with their own radar sets.

GCL. Ground control of the landing of aircraft.

Ghost signals. Signals appearing on the screen of the radar indicator, the cause of which cannot readily be determined.

GL. Gun laying. Information supplied by GL equipment (range, bearing, and elevation) is used to direct guns and to control their firing.

Glide path. The radar beam for flying or instrument landing of aircraft.

Grass. See Noise.

Grid pulsing. A circuit arrangement of the r-f oscillator in which the grid of the oscillator is biased so negatively that no oscillations take place even when plate voltage is applied to the tube, and pulsing is accomplished by removing this negative bias through the application of a positive pulse on the grid.

Grounded-grid triode mixer. The triode in which the grid forms part of a grounded electrostatic screen between the anode and cathode. It is used as a mixer for centimeter wavelengths.

Ground clutter. See Ground return.

Ground return. Radiation which is reflected from the ground and is returned as an echo to the radar set.

G-scan. A single signal only, appearing as a bright spot on which wings grow as the distance to the target is diminished. Azimuth angle appears as the horizontal coordinate, elevation angle as the vertical coordinate. This has been referred to as Mark VI indication.

G-scope. See G–scan.

Guide wavelength. The wavelength of electromagnetic energy conducted in a waveguide. The guide wavelength for all air-filled guides is always greater than the corresponding free-space wavelength.

Guillemin line. The network used in high-level pulse modulation in generating a nearly square pulse with steep rise and fall.

Gyroscope. An instrument which utilizes a rotating mass to maintain a stable equilibrium.

Helical scanning. The scanning motion in which a point on the r-f beam describes a distorted helix. The antenna rotates continuously about the vertical axis while the elevation angle changes slowly from the horizontal to the vertical.

Hollow space oscillator. See Cavity resonator.

Homing. The process of flying toward a transmitting station by means of a radio direction finder or radar. Also homing on a target in a radar-equipped aircraft.

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Horn radiator. An antenna shaped like a horn.

Hot magnetron. A magnetron generating r-f energy.

H-scan. A modification of B-scan. Signal appears as a bright line the slope of which is proportional to the sine of the angle of elevation. Azimuth appears as the horizontal coordinate, and range as the vertical coordinate.

H-scope. See H-scan.

I-F. See Intermediate frequency.

IFF. Identification of friend from foe. System used in conjunction with radar for distinguishing between friendly and enemy aircraft or surface vessels.

Indicator gate. A rectangular voltage to the grid or cathode circuit of an indicator cathode-ray tube to sensitize it during the desired portion of the operating cycle.

Instantaneous. A qualifying term indicating that no delay is purposely introduced in the action of the device.

Intensity modulation. The method of signal indication on a cathode-ray tube used in certain types of radar indicators, such as types B, C, and PPI, in which the grid or cathode of the CRT is connected to the output of the final video amplifier. During the sweep time the CRT is biased just beyond cut-off and video signals intensify the tube, producing bright spots to indicate the targets.

Interlock. A switch placed in the door of a cabinet, which must be closed before this switch will make contact and permit the high voltage to be thrown on.

Intermediate frequency (*i-f*). The frequency which is the difference between that of the magnetron (or transmitter) tube, and the local oscillator tube. In radar the intermediate frequencies range from 15 to 60 megacycles per second.

Intensity gate. See Indicator gate.

Interrogator responsor. A unit in the identification system which consists of a transmitter interrogator and receiver response operating on IFF frequencies and synchronized with some type of radar equipment. The receiver is designed to receive the signal from the IFF equipment on the ship or plane interrogated and apply that signal to the radar indicator.

I-scan. Used to depict range and direction for a system with a conically scanning antenna. Signal appears as a bright circular segment with radius proportional to range. The circular length of the segment is inversely proportional to the error of aiming this system and its position indicates the bearing of the target. True aim results in a complete circle. Also referred to as RTB indication.

I-scope. See I-scan.

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Isolating diode. A diode used to pass signals in one direction through a circuit but which prevents signals and voltages from being transmitted in the opposite direction.

Jamming. Intentional interference with normal operation of radio communication or radar equipment.

Jitter. Instability of the signal on the CRT screen.

J-scan. A modification of type A in which the time sweep produces a circular range scale near the circumference of the CRT face. The signal appears as a radial deflection of the time trace. No bearing indication is given.

J-scope. See J-scan.

Junction box. An inclosed distribution panel for connecting or branching one or more corresponding elecric circuits without the use of permanent splices.

Keep-alive. An auxiliary electrode in the T-R switch, to which a negative d-c potential is applied. The keep-alive is turned on before the main r-f power, and furnishes sufficient ions for almost instantaneous discharge across the main gap with small leakage power to the crystal.

Klystron. A tube in which oscillations are generated by the bunching of electrons (i. e., velocity modulation). This tube utilizes the transit time between two given electrodes to deliver pulsating energy to a cavity resonator in order to sustain oscillations within the cavity.

K-scan. A modification of type A-scan for aiming a double lobe system in azimuth (elevation). A horizontal (vertical) time sweep is displaced slightly in the direction of the antenna lobe in use. The signal appears as a double vertical (horizontal) deflection of the time sweep with the ratio of amplitudes indicative of the error in aiming.

K-scope. See K-scan.

Land return. See Ground return.

Leaky waveguide. A waveguide with a narrow longitudinal slot permitting a continuous energy leak.

Lighthouse tube. GL446 and GL464, parallel element tubes. When used in a suitable cavity combination, is useful as an r-f amplifier and oscillator in the microwave region.

Limiter. A circuit which limits or clips either or both the positive or negative portion of a waveform at a predetermined level.

Linear scan. A radar beam which transfers one arc or circle only.

Line balance converter. See Bazooka.

Line-of-sight coverage. The distance to which radar and television sets are, in general, limited, that is, do not follow the curvature of the earth, like broadcast radio. Refraction effects on radar beams,

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similar to mirage effects observed with visible light, can take place under certain atmospheric conditions.

Line-of-sight stabilization. A method of compensating for roll and pitch of the vessel or aircraft by changing the elevation of the spinner in order to keep the radar beam pointed at the horizon.

Lobe switching. Directing an r-f beam rapidly back and forth between two positions. Used for accurate direction finding.

Local indicator. Radar operator's indicator as contrasted with remote indicator for pilot or navigator.

Locking. (1) Controlling the frequency of an oscillator by means of an applied signal of constant frequency.

(2) Automatic following of a target, by a radar antenna.

Loran. Radio system for long-range navigation.

Lossy line. A cable having large attenuation per unit length.

L-scan. A modification of type A-scan for aiming a double-lobe system in azimuth (elevation). A vertical (horizontal) time switch indicates range. The signal from the left (lower) lobe appears as a horizontal (vertical) deflection to the left (downward); the signal from the right (upper) lobe as a horizontal (vertical) deflection to the right (upward). The ratio of signal amplitudes is indicative of the error in homing. British Mark IV.

L-scope. *See* L-scan.

Magnetron. A transmitter tube which produces the main pulse of ultra-high frequency energy. The flow of electrons is controlled by an applied magnetic field.

Main bang. *See* Transmitter pulse.

Main pulse. *See* Transmitter pulse.

Master multivibrator. A master oscillator using multivibrator circuit.

Master oscillator. A timing oscillator which controls other circuits.

Matching diaphragm. A window consisting of an aperture (slit) in a thin piece of metal, placed transversely across the waveguide; used as a matching device. The orientation of the slit (whether parallel to the long or short dimension of the waveguide) determines whether it is respectively capacitive or inductive.

McNally tube. A local oscillator tube. A single-cavity, velocity-modulated tube, the frequency of which may be controlled over wide ranges by electrical methods. (*See* Klystron.)

Megacycle. One million cycles. Often used conversationally to mean megacycles per second.

Microsecond. One-millionth of a second.

Microwaves. Radio waves, the length of which is less than approximately 1 meter.

Mixer. The stage of a microwave amplifier circuit, into which the signal voltage and a voltage from a local oscillator are fed, and from

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which the i-f comes out to the first stage of the i-f amplifier. Common mixers are crystal mixers and diode mixers. They are made in such a form that they can be inserted in the transmission lines which are used for the r-f circuits.

Mock-up. (1) A dummy airplane built for study of structural and interior arrangements prior to the construction of a real model.

(2) A dummy radar set, or part of a set, built for a preliminary study of the arrangements of components.

Mode. Different types of electromagnetic waves that may be sustained in a given resonant system. Each type of vibration is designated as a particular mode, and has its own particular electric and magnetic field configuration.

Modulator. The part of the radar set which controls the application of plate voltage to the transmitter.

Modulator driver. See Driver.

Monitor. To perform a check on a given system by measuring or observing voltages, or waveforms, or recurrence rate.

Monitoring antenna. Used to pick up r-f output, for purposes of checking the system.

M-scan. A modification of type A-scan for accurate range finding. A horizontal time sweep is displaced slightly vertically stepwise. The signal appears as a vertical deflection of the time sweep. An auxiliary device for controlling the phase of the signal or the step is used to bring them into coincidence, at which point the device registers range.

M-scope. See M-scan.

Multivibrator. A form of relaxation oscillation, essentially a two-stage amplifier with feedback. Will oscillate of its own accord, or as a result of the application of an external synchronizing voltage.

Noise. A random voltage appearing at the output terminals of the receiver with no impressed signal, if the amplifier has sufficient gain. On the A-scope, noise appears as random spikes (grass) on the sweep line. It is due to random motion of electrons in the grid circuit of the first amplifier tube, to fluctuations in emission, shock noise at the plate, etc.

North-stabilized PPI. Used in conjunction with a gyro compass, to keep the PPI pattern oriented to true north, and does not change when the direction of the ship or aircraft alters. (*See* Azimuth-stabilized PPI.)

N-scan. A combination of type K- and M-scan.

N-scope. See N-scan.

Overshoot. An excessive potential attained by a portion of the main body of a pulse. Compare Back swing and Tail.

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Own ship's course bus (*O. S. C.*). The cable which feeds the output of a selsyn generator controlled by the ship's gyro compass to the radar set for producing indication of true bearing.

Pantograph (radar). System for transmitting and automatically recording data from CRT to a remote point.

Paraboloid. A reflecting surface formed by rotating a parabola about its axis of symmetry. Paraboloidal reflector or dish.

Peaking circuit. A circuit used to sharpen a wave of any form, whereas a differentiating circuit is designed to sharpen a square wave.

Pencil beam. A radar beam in which energy is confined to a narrow, approximately conical portion of space.

Pencil mixer. A form of crystal mixer.

Phanatron. A precision delay circuit.

Phantom signals. *See* Ghost signals.

Phantom target. *See* Echo box.

PᵉI. Expanded PPI presentation.

Pill box antenna. A narrow cylindrical parabolic antenna, with plain parallel ends.

Pip. A term used to designate a signal or special marker on the A-scope type of presentation.

Plan repeater indicator. *See* Remote indicator.

Plate pulsing. A circuit arrangement of the r-f oscillator in which the plate voltage is normally reduced to such a low value or completely removed, so that no current flows to the plate and no oscillations occur. A pulse equal to the full plate voltage is then introduced in series with the plate. Oscillations begin and last for the duration of the pulse. This circuit requires a modulator capable of supplying full plate power.

Plumbing. A term used to designate waveguides or coaxial lines and accessory equipment for the transmission of r-f energy.

Plunger. *See* Waveguide plunger.

Polyplexer (aircraft). A system for combining the operations of both duplexing and lobe switching in certain radar equipments.

Polyrod antenna. An antenna in which the radiating element is a rod of polystyrene. Similar to the action of a leaky waveguide.

Potted line. A pulse-forming network immersed in oil and inclosed in a metal container.

PPI-scan. Plan position indicator. The sweep is a radius of the tube face (from center of face), and moves around through 360°. It gives azimuth by direction of the radial line, and range by the distance of the signal from the center of the screen.

PPI-scope. *See* PPI-scan.

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Preamplifier (*pre-amp.*). A small unit containing the first two or three stages of the radar receiver. It is located near the mixer so that the i-f signal is at high enough level to be transmitted over appreciable distances to the remainder of the receiver without being affected by extraneous noise.

Precision sweep. A small portion of a normal sweep, usually 2,000 yards, selected and expanded over the entire screen in order to permit precise range measurements.

Presentation. The form which the radar echo signals are made to take on the CRT screen, which is dependent upon the nature of the sweep circuit utilized. Examples: A-scan presentation, PPI-scan presentation, etc.

Present range. See Range.

Pressurized component. The filling of a radar component with dry air or other gases at a pressure greater than atmospheric. Its purpose is to prevent break-down of the component at high altitudes, and to protect against transmission losses caused by materials in the atmosphere, such as dirt and water.

PRF. Pulse recurrence frequency. (*See* Repetition rate.)

Probe. A projecting rod placed in the slotted section of an r-f line and used to pick up r-f energy, in the determination of standing-wave ratio.

P-scan. See PPI-scan.

P-scope. See PPI-scan.

Pulse. A sudden change of voltage or current of short duration.

Pulse amplifier. Video amplifier which amplifies the pulse waveform without materially affecting its shape.

Pulse oscillator. An oscillator which is made to operate repetitively, usually at a low-duty cycle (i. e., having the pulses short compared with the intervals between them).

Pulse-forming line. A combination of inductors and capacitors used to produce a square pulse of controlled duration.

Pulse-modulation system. Radar system in which the transmitter is turned off before the reflected energy arrives back from the target.

Pulse rate. See Repetition rate.

Pulse repetition frequency. See Repetition rate.

Pulse transformer. A special transformer designed to have a frequency response suitable for passing a pulse without materially altering its shape.

Pulse width. The time duration of a pulse as measured at half amplitude.

Racon. A radar beacon.

Radar. An abbreviation for radio direction and ranging.

Radar range. See Range.

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Range. Distance from the radar set to the object giving an echo.

Radar test scope. A combination synchroscope and oscilloscope provided with fast sweeps, which enables the examination of waveforms and voltages throughout the radar set.

Radome. A general name for radar turrets which inclose antenna assemblies.

Range mark. A mark on the CRT screen which indicates distances from the radar set of the various echoes appearing on the screen of the CRT.

Rapid scanning. The use of narrow beams in the horizontal plane, scanned 10 cycles per second or higher for application to gun-laying radar.

Rate of change of bearing. Bearing rate; azimuth rate. The rate at which bearing (true or compass) is changing with respect to time as a result of relative motion between target and antenna position. It may be stated in degrees per second, or in other units of angular measure.

Rate of change of compass bearing. The rate at which compass bearing is changing with respect to time, as a result of relative motion.

Rate of change of true bearing. True bearing rate; azimuth rate. The rate at which true bearing is changing with respect to time, as a result of relative motion.

RCM. Radar counter measures.

RDF. Radio direction finding. British abbreviation for radar.

Receiver gating. Applying operating voltages to one or more stages of intermediate frequency amplification in a receiver during that part of a cycle of operation when reception is desired.

Recovery time. (1) Of receiver: The time required for the receiver to recover to half sensitivity, after the end of the transmitted pulse.

(2) Of T-R switch: Time required after an r-f pulse has fired the gap in the T-R switch, for the received signal to reach half its maximum amplitude.

Recurrence rate. See Repetition rate.

Reference voltage (servo systems). The a-c live voltage used to determine the in-phase or 180° out-of-phase condition of the selsyn error voltage in order to provide a directional sense to the servo system.

Reflex klystron. See Klystron.

Relative bearing. Bearing measured relative to the heading of vessel or aircraft. Measured clockwise from 0° to 360°.

Remote indicator. Additional indicator located at a station remote from the operator's equipment.

Repetition frequency. See Repetition rate.

Repetition rate. The rate (usually given in cycles per second) at which pulses are transmitted from the radar set.

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Reprod. See Duplexing assembly.

Resolution in azimuth. The angle by which two targets must be separated in azimuth in order to be distinguished by the radar set, when the targets are at the same range.

Resolution in range. The distance by which two targets must be separated in range in order to be distinguished by the radar set, when the targets are on the same line of bearing.

Resonant charging choke. In modulators, denotes the inductor, which, with the effective capacitance of a pulse-forming network, is used to set up an oscillation of a given charging frequency.

Resonator. See Cavity resonator.

Responsor. See Interrogator responsor.

RF-IF converter. See Preamplifier.

Rhumbatron. See Cavity resonator.

Rotary spark gap. A device in which several electrodes mounted on a wheel are rotated past a fixed electrode producing spark discharges periodically.

Rotating joint A device for permitting one section of a transmission line to rotate continuously with respect to the other and still maintain electrical continuity.

RTB indication. See I-scan.

R-T box. See Anti-T-R switch.

R-T switch. See Anti-T-R switch.

S-. U. S. Navy prefix to designate shipborne search radar. Examples: SA, SC, SJ, etc.

Sand load. An attenuator used as a terminating section to dissipate power. The space between the inner and outer conductors of a coaxial line or in a waveguide is filled with a sand and carbon mixture which acts as a characteristic impedence.

Saturated signal. The maximum possible signal that may be observed on a scope due to saturation limiting in the video output of the receiver.

Saxaphone. A vertex-fed linear array antenna giving a cosecant-squared radiation pattern.

Scanning. The process of directing the r-f energy successively over all points in a given region or space.

SCI. Ship-controlled interception. Compare CCI.

SCR. U. S. Army prefix for Signal Corps radio and radar equipment. Examples: SCR–268, SCR–582, etc.

Searchlight control radar (SLC). Equipment for directing searchlights onto aircraft. Permits making interceptions by illuminating the aircraft. Also permits accurate antiaircraft fire through optical tracking.

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Searchlighting. Projecting the radar beam continuously at any given object or target, instead of illuminating it once during each scan period.

Sea-return. A signal reflected back from the sea.

Seasoning. Overcoming a temporary unsteadiness of the magnetron which may appear when it is first installed.

Sector scan. Motion of the antenna assembly back and forth through a limited angle. In contrast to continuous (360°) rotation.

Selectivity. The ability to discriminate between radio waves of different frequencies.

Self-synchronous. *See* Selsyn.

Selsyn. A single-phase self-synchronous machine which converts mechanical position into electrical signal, or vice versa.

Selsyn generator. A selsyn which has an electrical output proportional to the position of its rotor. (*See* Selsyn.)

Selsyn motor. A selsyn in which the rotor-shaft position is dependent upon the electrical input. (*See* Selsyn.)

Selsyn receiver. Term sometimes used to designate a selsyn motor.

Selsyn transmitter. Term sometimes used to designate a selsyn generator.

Sensitivity. A measure of the minimum signal to which a device shows a measurable response.

Servo system. A complete electromechanical system for amplifying and transmitting accurate mechanical position from one point to another by electrical means.

Sheppard tube. The Sheppard-Pierce tube, a trade name for an all-metal velocity modulation tube. (*See* Klystron.)

Side bands. When the amplitude or frequency of a high-frequency wave is varied at a comparatively low rate, the high-frequency wave is said to be modulated. The resultant wave has a component of the high-frequency plus other frequencies that depend on the modulation. These are the side bands.

Side lobe. A portion of the beam from a radar antenna, other than the main lobe, and usually much smaller.

Signal-to-noise ratio. The ratio, at any point of the circuit, of signal power to total circuit-noise power.

Silver bullet. A silver-plated, bullet-shaped connector, for joining two similar coaxial lines.

Single-stub tuner. A short section of transmission line terminated by a movable short-circuiting plunger or bar. It is attached to the main transmission line as an impedence-matching device.

Skitron. A color trace tube for projecting purposes. (*See* Dark trace tube.)

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Slant range. The distance from a position on the ground to an aircraft or to any other object not at its own level. Used in contrast to ground range.

Slotted section. A slot in a transmission line along which a probe is moved, to measure standing-wave ratio.

Sparkgap. An arrangement of two electrodes between which a disruptive discharge of electricity may take place, and such that the insulation is self-restoring after the passage of a discharge.

Spark-gap modulator. A modulator in which the high-current switch takes the form of a spark gap. The spark gap may be either of the triggered or the rotary type.

Spark-pulse modulator. See Sparkgap modulator.

Spectrum analyzer. A test instrument used to show the distribution of the energy contained in the frequencies emitted by pulsed magnatrons; to measure the Q of resonant cavities or lines; and to measure the cold impedance of a magnetron.

Spinner. The antenna assembly, including antenna, reflector, mount for the reflector, motors, etc.

Spiral scanning. A type of antenna rotation in which a point on the r-f beam traces out a spiral. Only a small sector in the desired direction is illuminated.

Spun barrel reflector. A type of reflector used for producing a beam narrow in azimuth, which illuminates fairly uniformly a wide strip of terrain.

Squeezable waveguide. A waveguide used in rapid scanning, the dimensions of which can be altered periodically.

SSV. Ship to surface vessel. Radar to detect surface vessels from patrol surface craft.

Stabilization (radar). A system for maintaining a radar beam in a desired direction in space despite the roll and pitch of the ship or aircraft.

Stable element. A gyroscopic instrument which maintains a true vertical, and develops angles of deviation of the ship's deck or aircraft from the true horizontal. It normally develops roll angle and pitch angle, or level and cross level. The stable element provides input data to all computers or stabilization systems.

Standing wave. The resulting wave from the electric variation in a circuit caused by periodic exchange of energy between current and voltage forms without transmission of energy. In a radar set, a wave passing down the transmission line and striking an obstruction or meeting a mismatch is reflected and returns up the line. The reflected wave combines with the initial radiant wave to form the standing wave. Such standing waves result in increased losses, and should be kept to a minimum.

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Standing-wave detector. An instrument containing a detecting device (bolometer, thermocouple or crystal) which enables one to determine the ratio of the maximum voltage (current) to the minimum voltage (current) of the standing wave.

Standing-wave ratio. The ratio of current (or voltage) maxima to the current (or voltage) minima. It is determined by the load impedance and by the characteristic impedance of the line.

Stator. The portion of an electrical machine which contains the stationary parts of the magnetic circuit with their associated windings.

Stub-supported line. A type of coaxial transmission line in which the inner conductor is maintained coaxially with the outer conductor by the use of stubs. The stub consists of a short-circuited section of coaxial line.

Stub tuner. See Single-stub tuner; Double-stub tuner.

Sweep (time base). Trace produced on the screen of a cathode-ray tube by linear deflection of the electron beam. In radar, the time measured along the sweep is proportional to range since it normally starts with the beginning of the transmitter pulse. In some circuits the beginning of the sweep is delayed for a fixed or variable time after the firing of the transmitter. It is then known as a delayed sweep.

Synchro. See Selsyn.

Synchronism. The relationship between two or more periodic quantities of the same frequency when the phase difference between them is zero.

Synchronizer. See Timer.

Synchroscope (radar). An oscilloscope on which recurrent pulses or waveforms may be observed, which incorporates a sweep-generator that produces one sweep for each pulse, regardless of frequency, thus allowing no more than one cycle to be viewed on the screen.

Tail. (1) A small pulse, following the main pulse and in the same direction. Compare Back swing and Overshoot.
(2) Slow decaying, following main body of pulse.

Target. Any object producing a radar echo.

Three-phase selsyn. A misnomer. (*See* Selsyn.)

Tilt. The angle which the antenna forms with the horizontal.

Time base. See Sweep.

Time flutter. Variation in the synchronization of components of a radar system, leading to variations in the position of the observed pulse along the time base, and reducing the accuracy with which the time of arrival of a pulse may be determined.

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Timer. That part of the radar set that initiates pulse transmission and synchronizes this with the beginning of indicator sweeps, timing of gates, range markers, etc.

T-junction. The section of the transmission line between the transmitter to the antenna where it is joined by the transmission line from the receiver.

Tracking. Keeping the radar beams, or the cross hairs of an optical system, set on a target.

Train. To aim or direct the radar antenna in a horizontal plane.

Transmit-receive. See T-R switch.

Transmitter pulse. The main transmitted pulse, in a radar set. On the A-scan, it appears as a strong vertical pip at the extreme left end of the sweep.

Transpónder. The unit of the IFF system which receives the interrogator signal and automatically transmits the reply.

T-R box. See T-R switch.

T-R switch. Transmit-receive switch. A switch which prevents the transmitted energy from getting to the receiver, but allows the received energy, which is much weaker, to reach the receiver without appreciable loss. This is necessary when the same antenna is used for both transmission and reception.

Trigger pulse. A pulse which starts a cycle of operation.

Triggered spark gap. A fixed spark gap in which the discharge passes between two electrodes and is struck (started) by a subsidiary electrode, the trigger, to which low-power pulses are applied at regular intervals from a pulse amplifier, thus closing the switch.

Triggatron. High-pressure trigger spark-gap modulator.

Trip. See Trigger pulse.

True bearing (azimuth). Bearing measured relative to true north. The angle formed by the intersection of the line-of-sight and the true meridian passing through the observer's position. Measured clockwise at the position of the observer from the north point of the horizon; from 0° to 360°.

True-bearing rate. See rate of change of true bearing.

Truncated paraboloid. A paraboloid in which a portion of the top and bottom have been cut away in order to broaden the radar beam in the vertical plane.

Tunable echo box. An echo box consisting of an adjustable cavity operating in a single mode. If calibrated, the setting of the plunger at resonance will indicate the wavelength.

Turnstile antenna. Consists of two linear antennas, lying in a plane, and crossing one another without electrical contact at their centers. If the angle between the two is 90°, the length of each half a wave-

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length, and the currents 90° out-of-phase, the directional pattern in the plane of the radiators is approximately a circle.

Two-phase-selsyn. A misnomer. A special selsyn having two windings spaced at right angles to each other on the stator. These are excited with a single-phase power.

Valve. British term for a vacuum tube.

Video. The intelligence of a radar echo.

Video amplifier. An amplifier which has uniform response to signals of a very wide band of frequencies. (*See* Pulse amplifier.)

Warm-up drift. Change in frequency of an oscillator during the warming-up period.

Waveguide. A hollow pipe, usually of rectangular or round cross section used to transmit r-f energy. The dimensions of the pipe are determined by the wavelength to be transmitted.

Waveguide elbow. A prefabricated bend in a waveguide.

Waveguide plunger. A piston which may be moved within a waveguide to provide a short circuit at any desired point in the guide.

Whisker. The sharpened metal wire in contact with the crystal of a crystal mixer.

Windshield. In radar, a streamlined cover placed in front of airborne paraboloid antennas to minimize wind resistance. The cover material is such as to present no appreciable attenuation to the radiation of the radar energy.

Wuerzburg. German fire-control radar.

Zero-time reference. Reference point in time from which the operations of the various radar circuits are measured.

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